Evaluating the imprint of planet formation on the compositions of stars

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Kunitomo et al. (2017a), *A&A*
Kunitomo et al. (2017b), *in prep.*

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Observatoire de la CÔTE d'AZUR

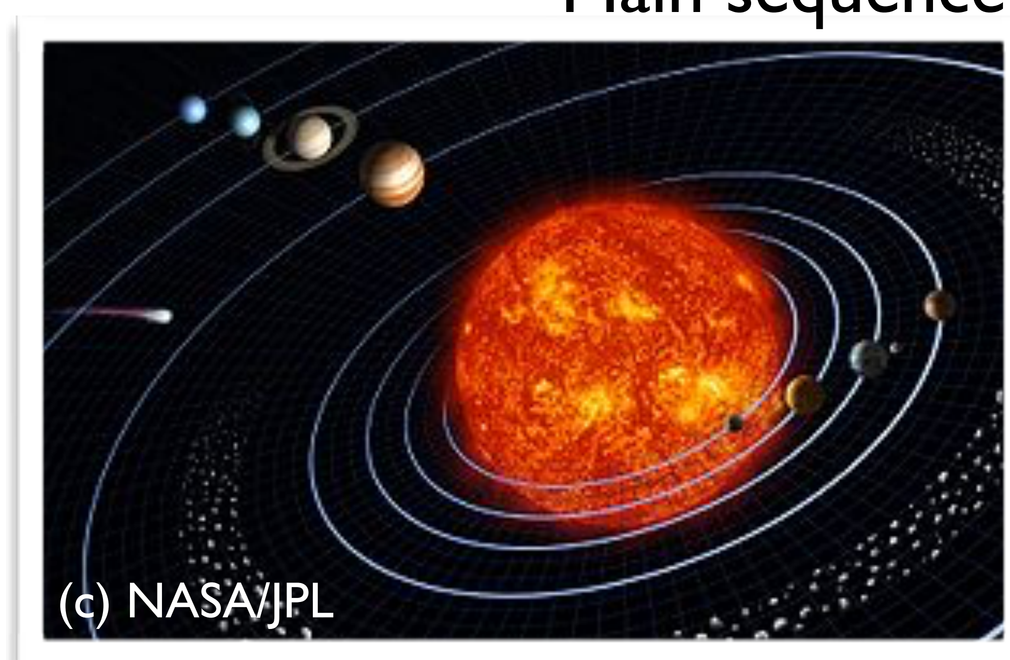
TOKYO TECH

June 20, 2017
Seminar at OCA

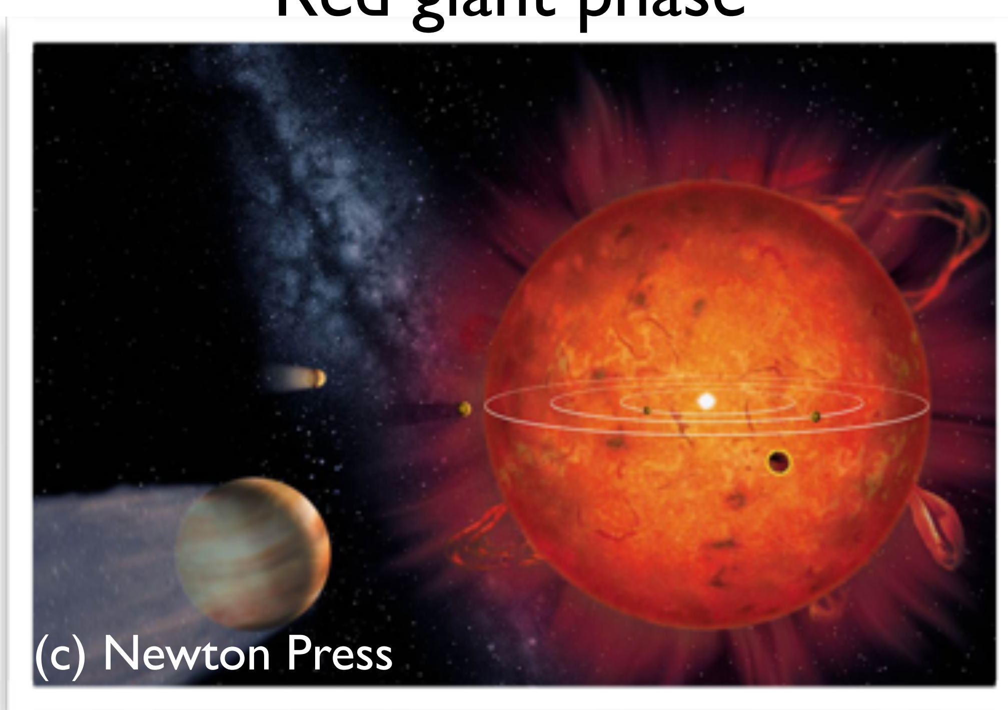
Molecular clouds

star/planet formation

Main sequence

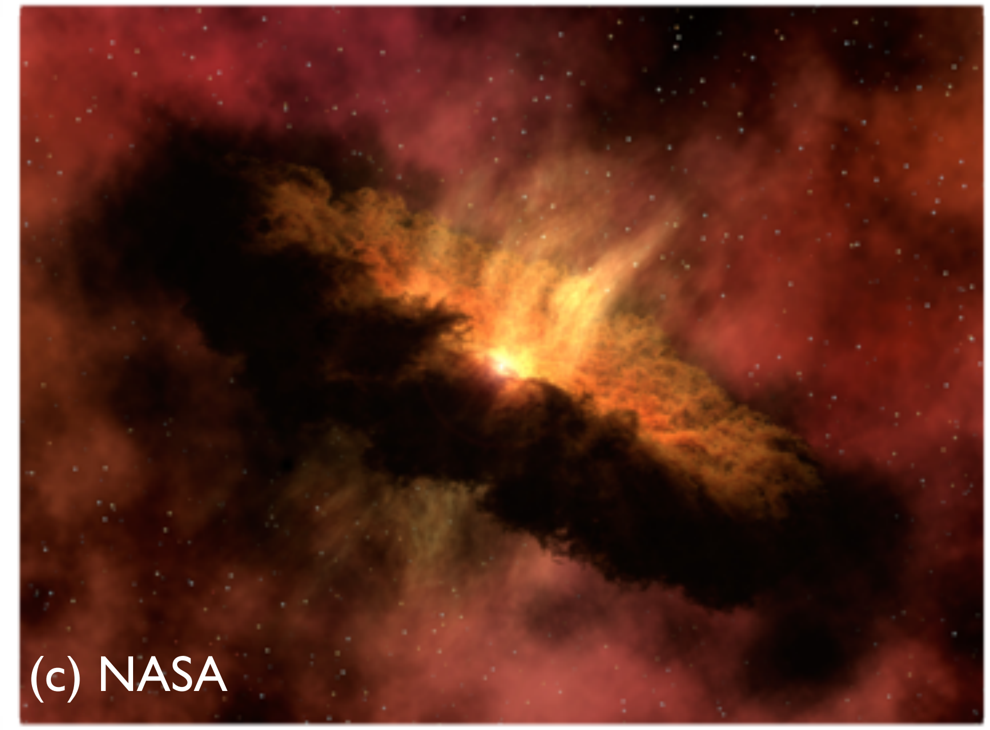


Red giant phase



Molecular clouds

star/planet formation



Kunitomo et al. (2017a), *A&A*
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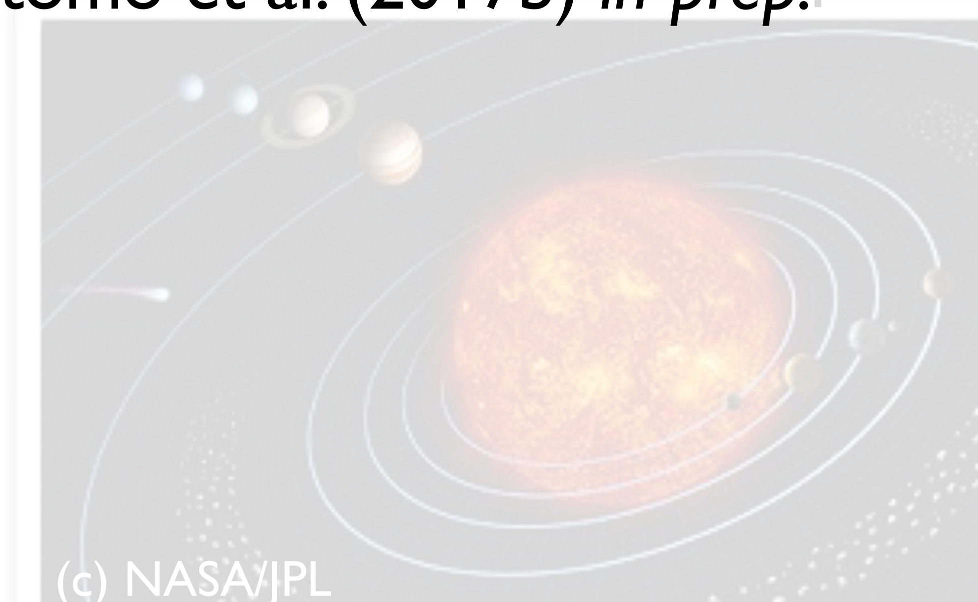
Main sequence

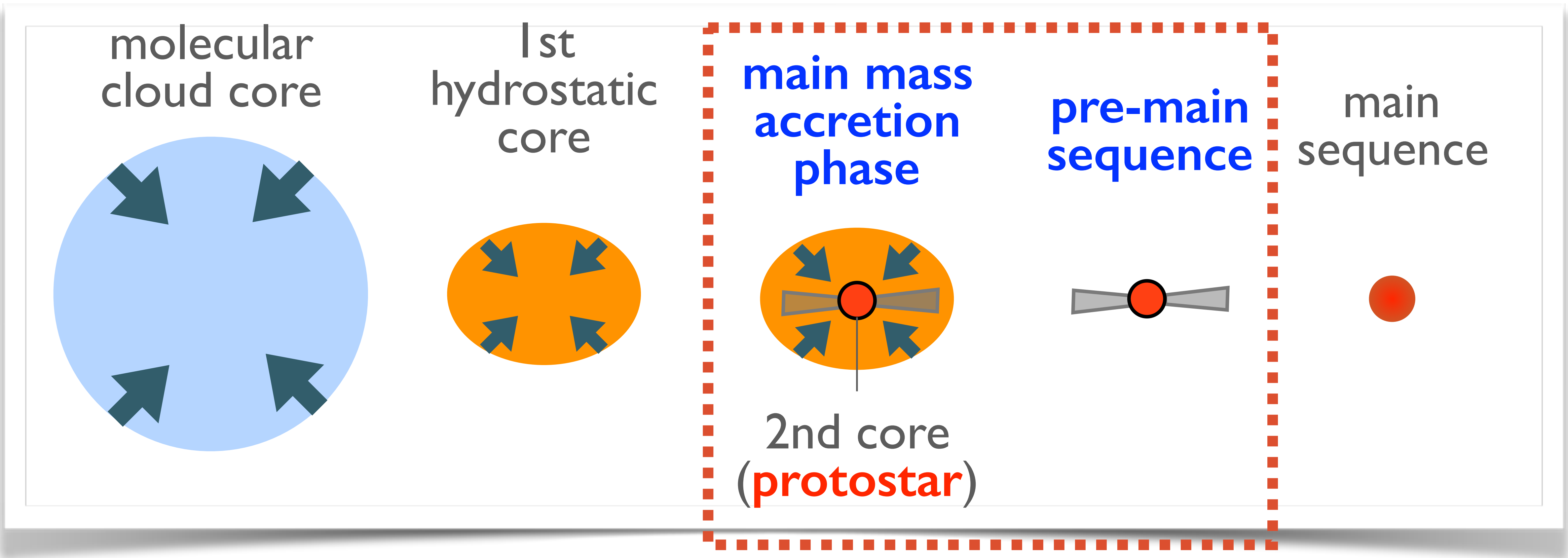


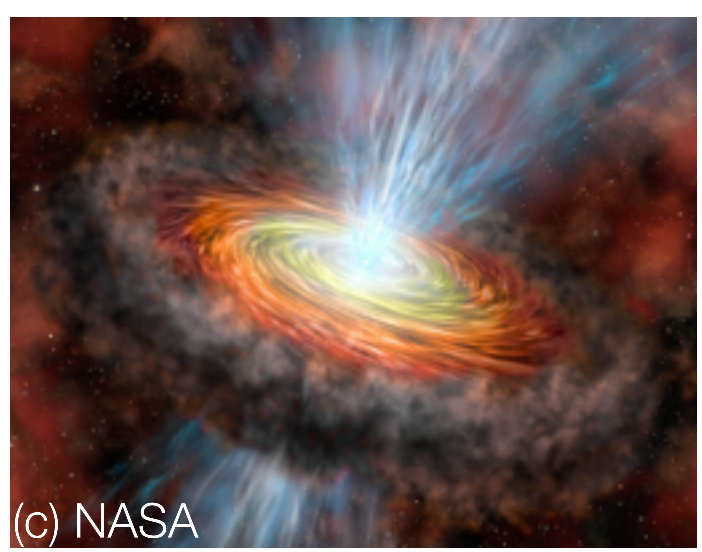
Red giant phase

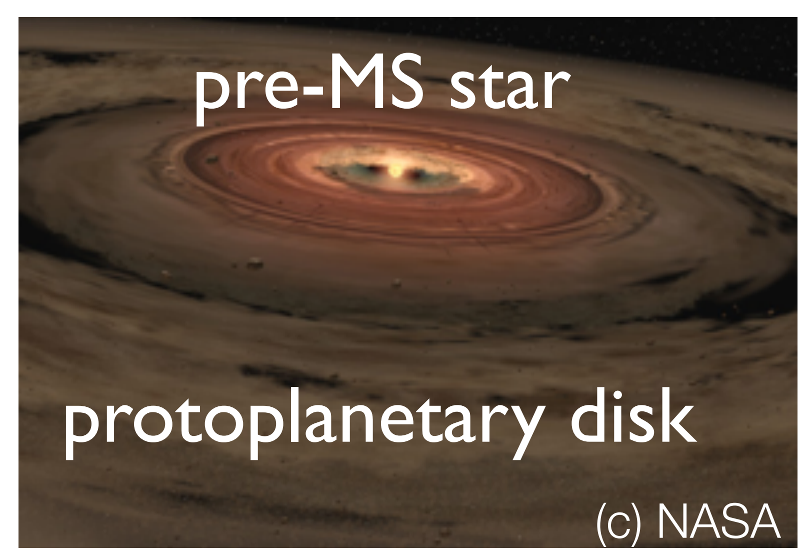
Standard picture of star formation

e.g., Larson69

* Underlying physics: Later

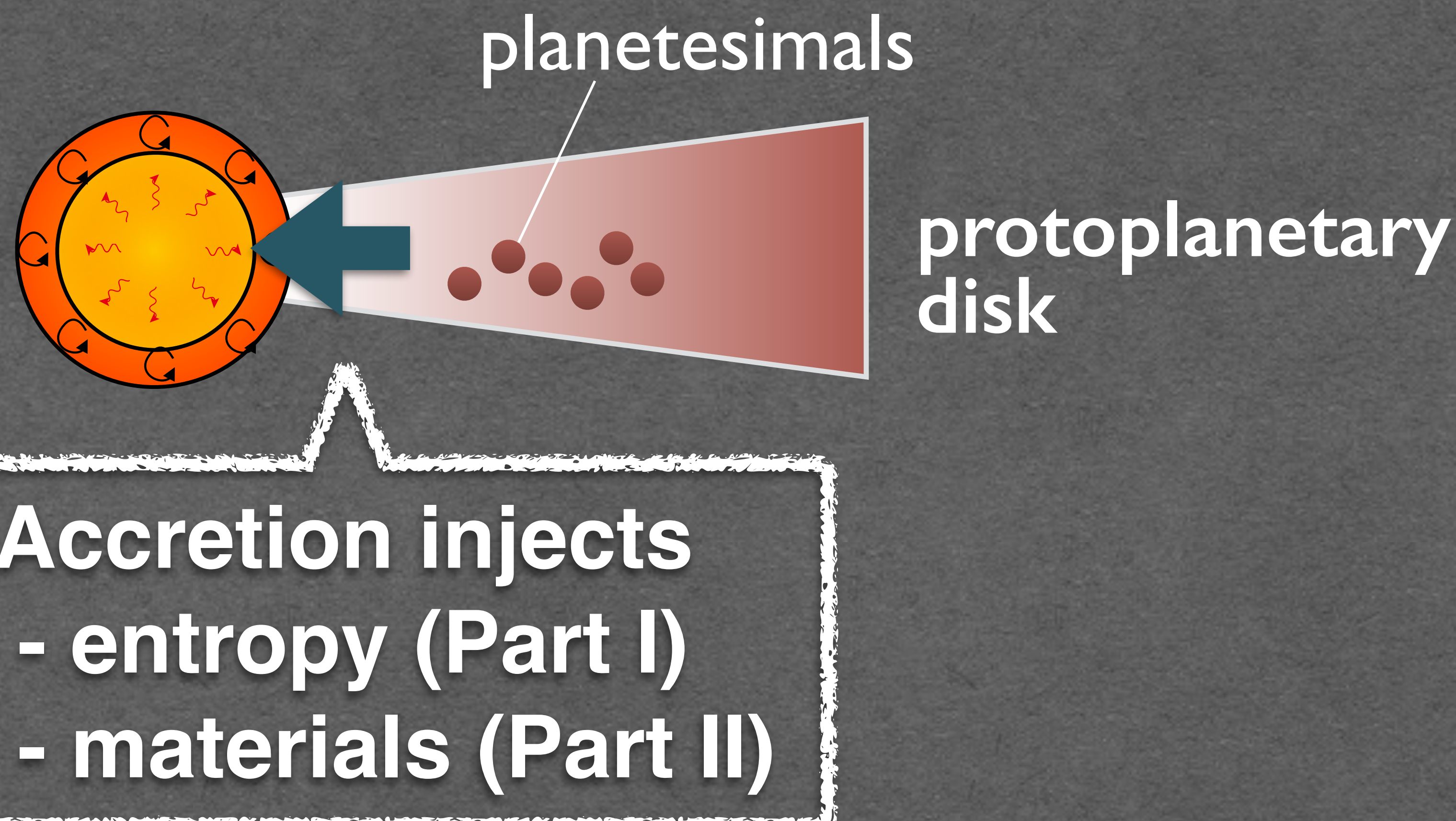




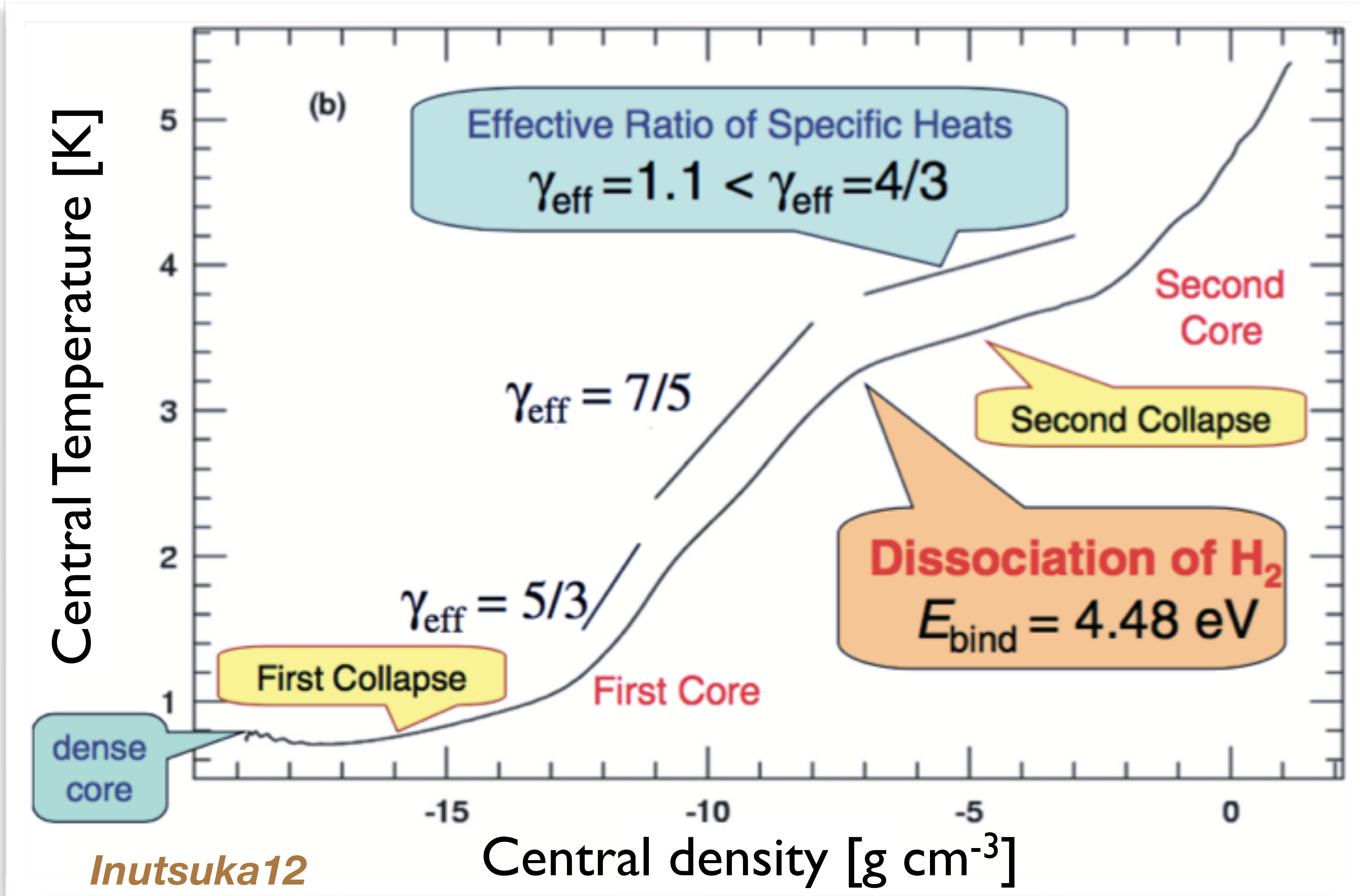


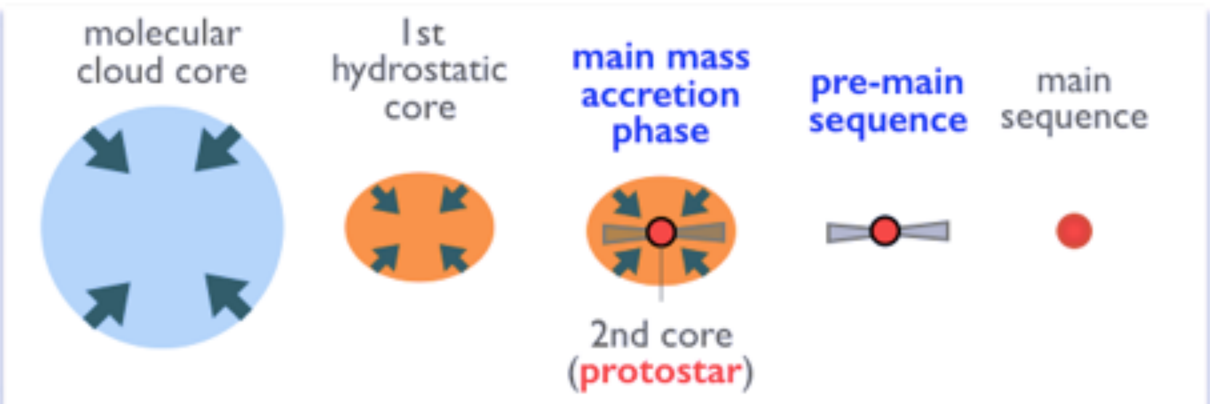
Question of this seminar:

Does accretion affect the thermal/chemical evolution of stars?

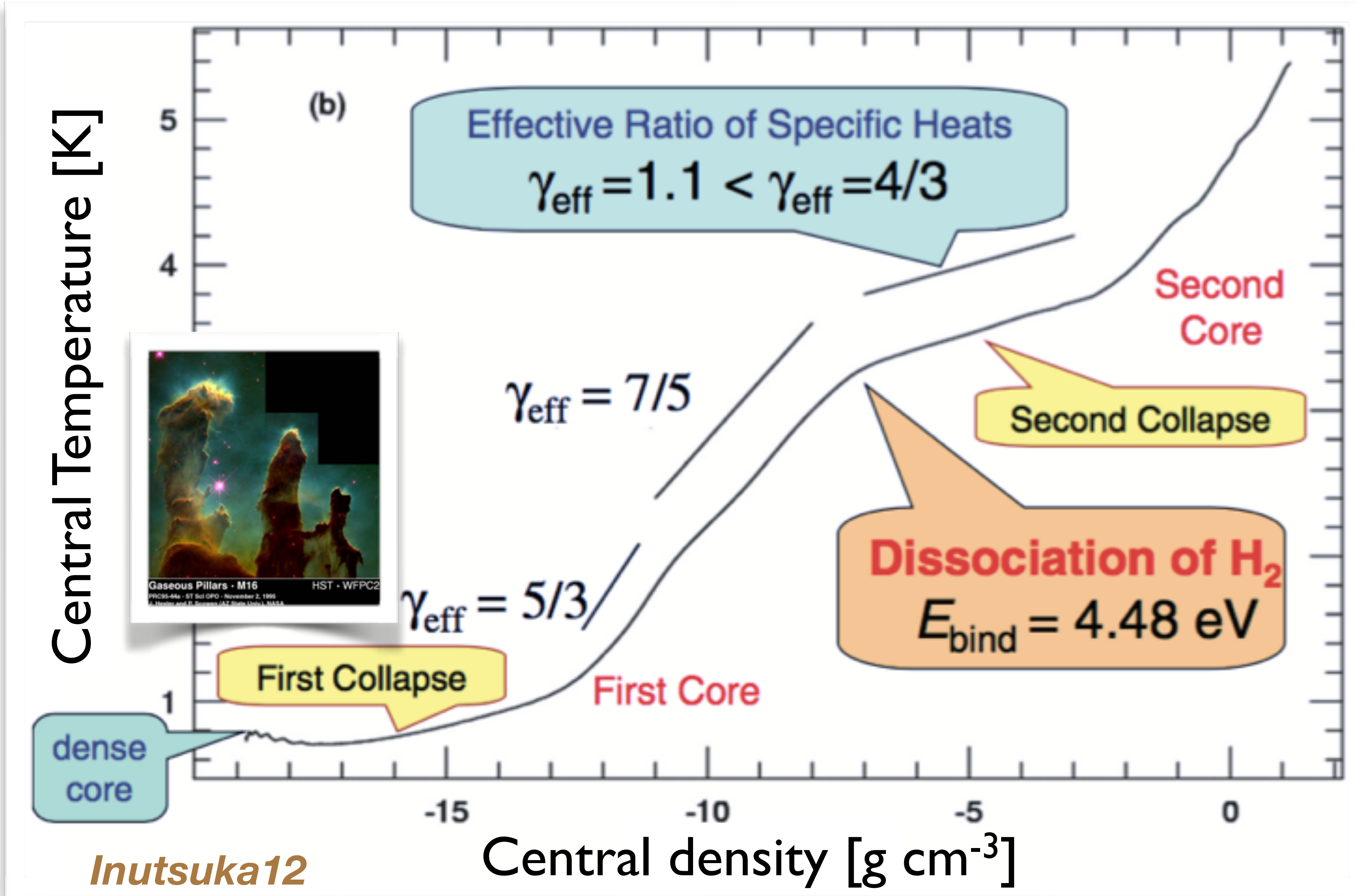


Basic physics of star formation

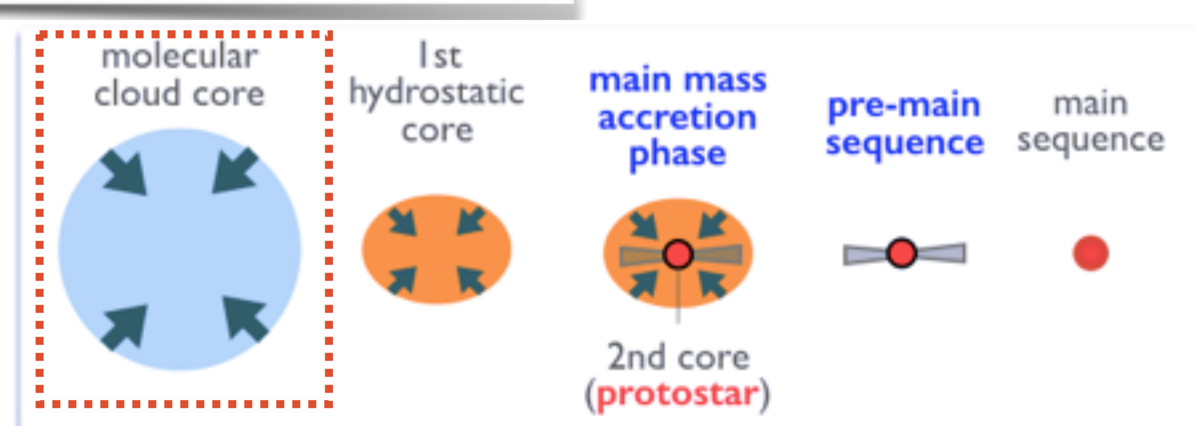




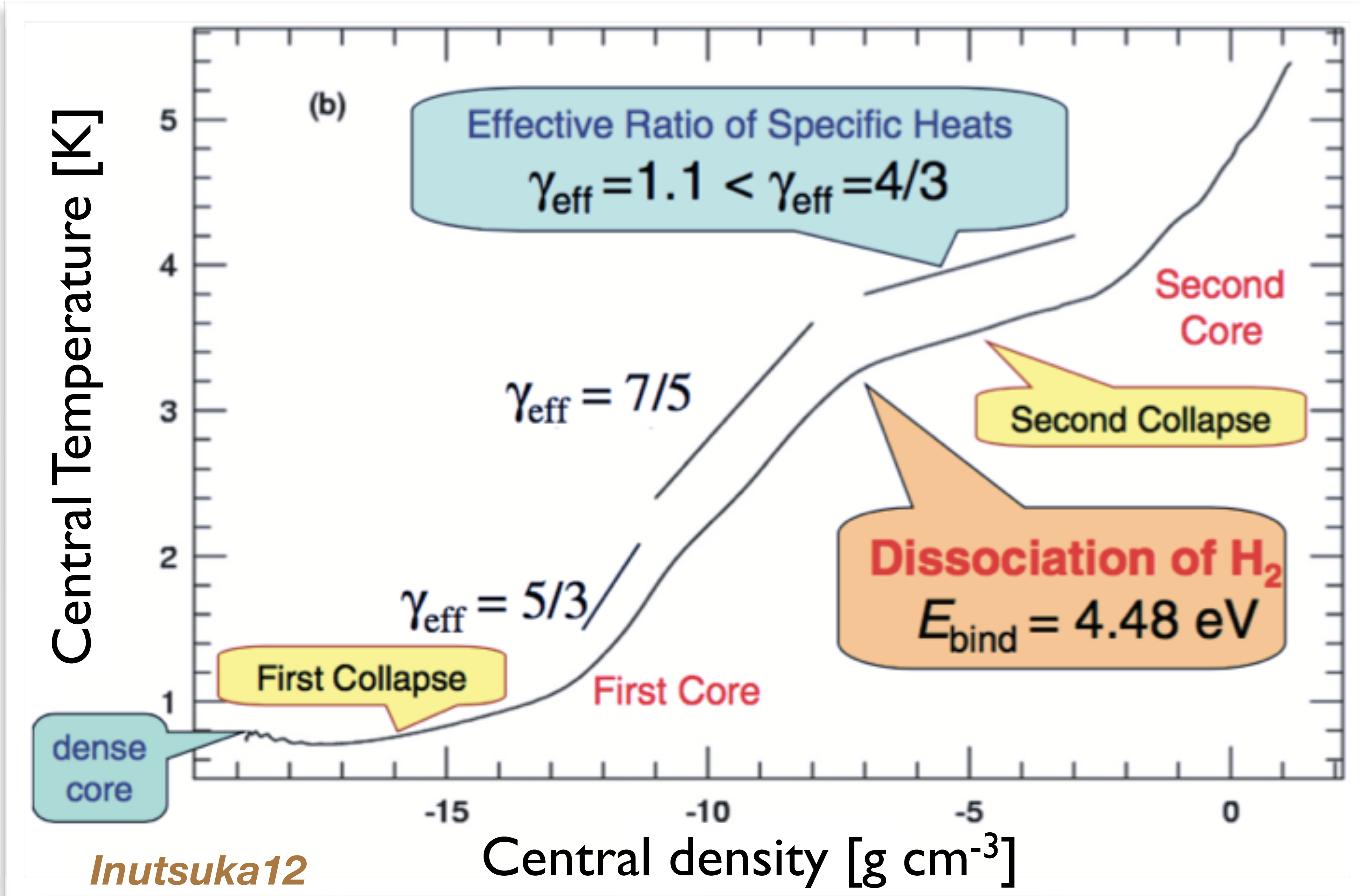
Basic physics of star formation



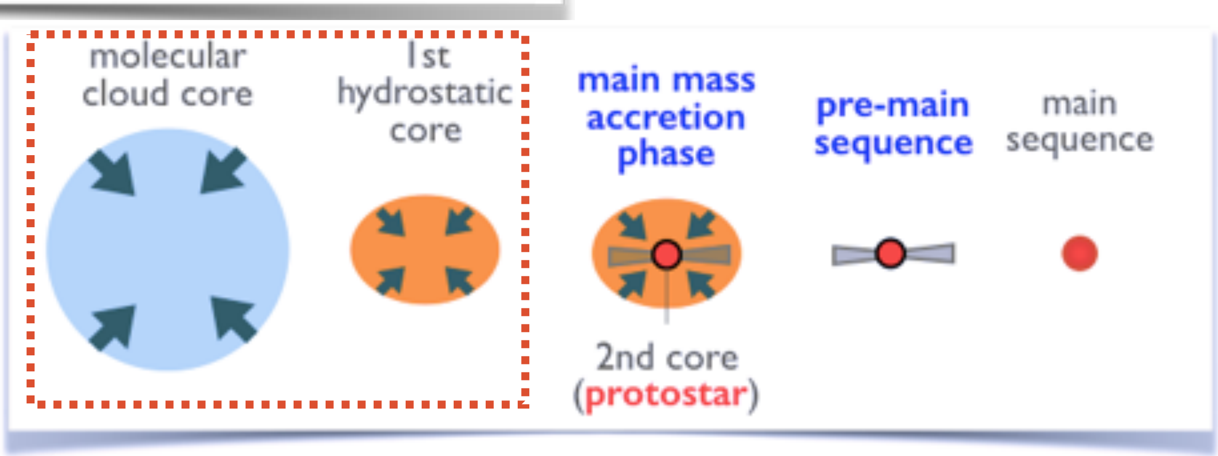
- Gravitational instability causes collapse
- Isothermal ~10K



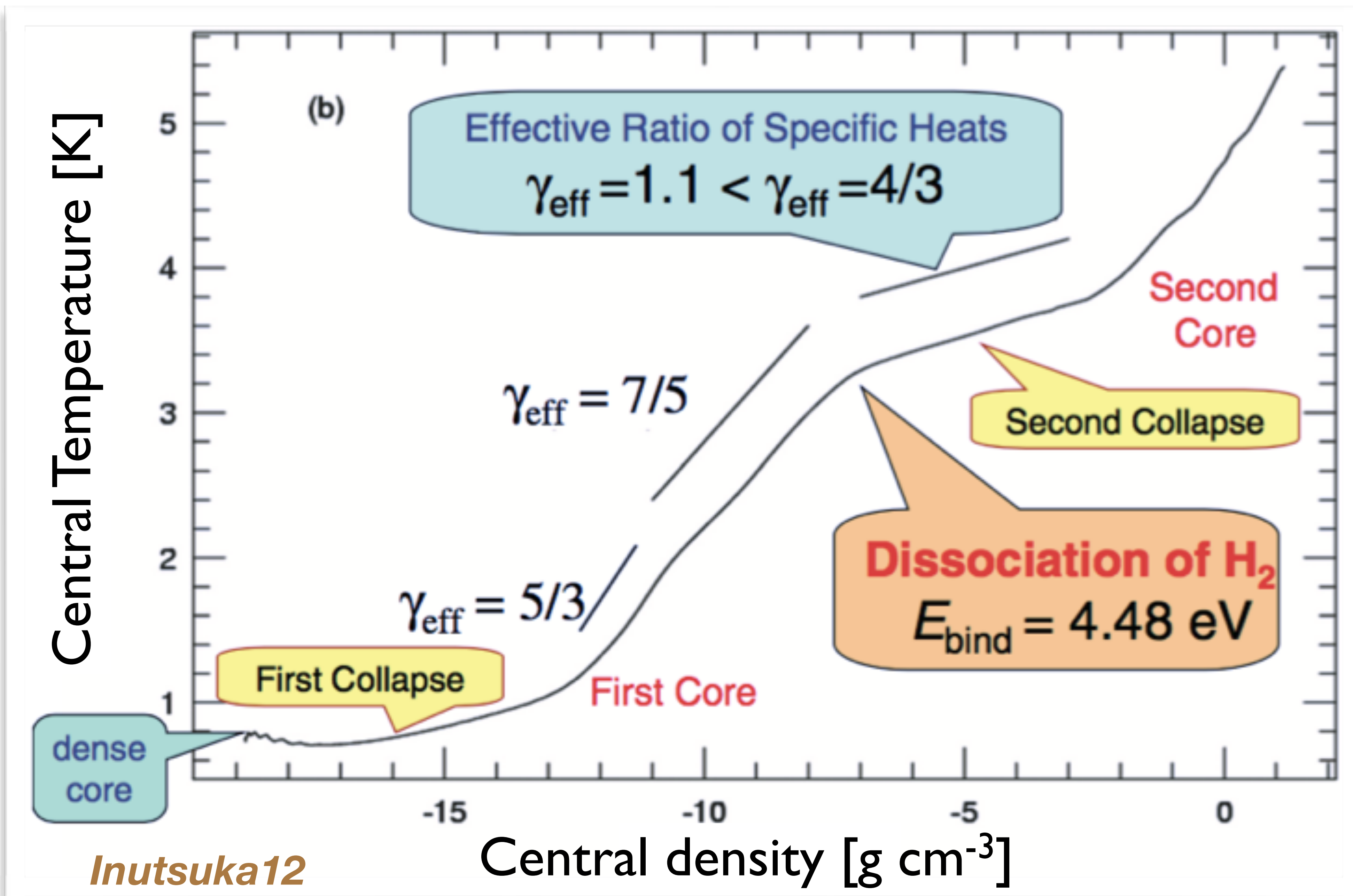
Basic physics of star formation



High internal density
➔ opaque
➔ high internal temp. and density
➔ pressure support (hydrostatic) core



Basic physics of star formation

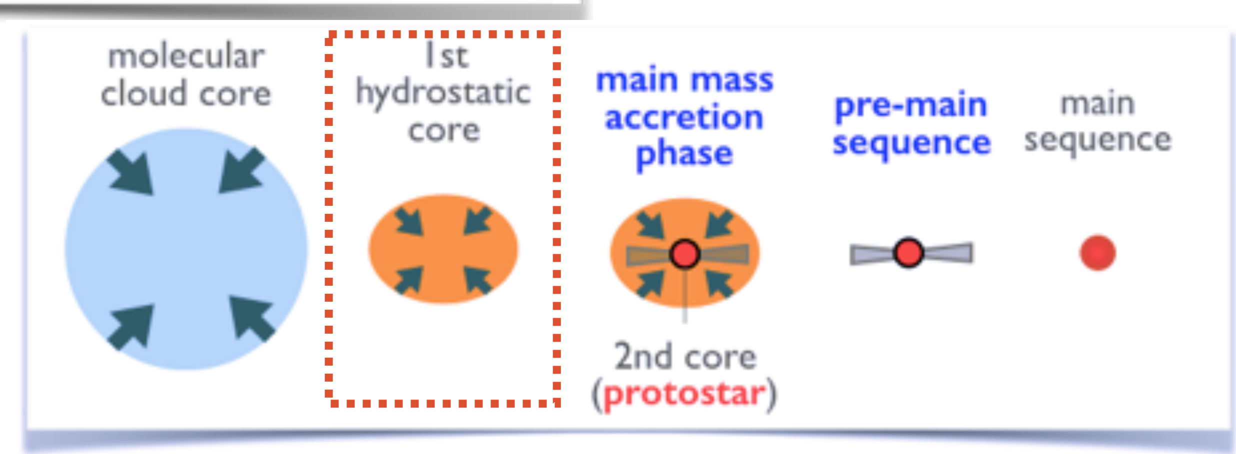


T≳2000K

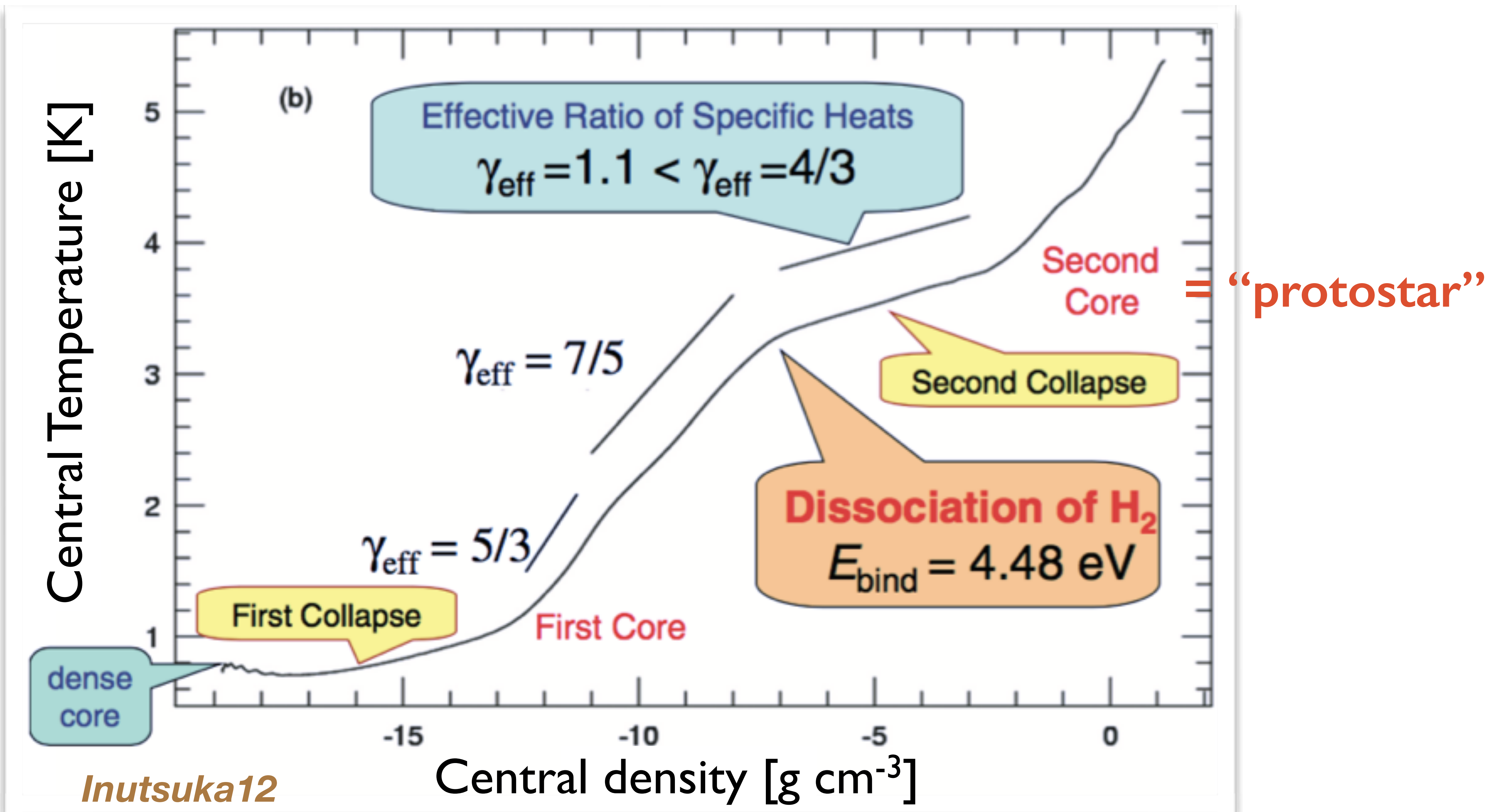
➔ H_2 molecules dissociate

➔ Strong endothermic reaction

➔ Collapse again!



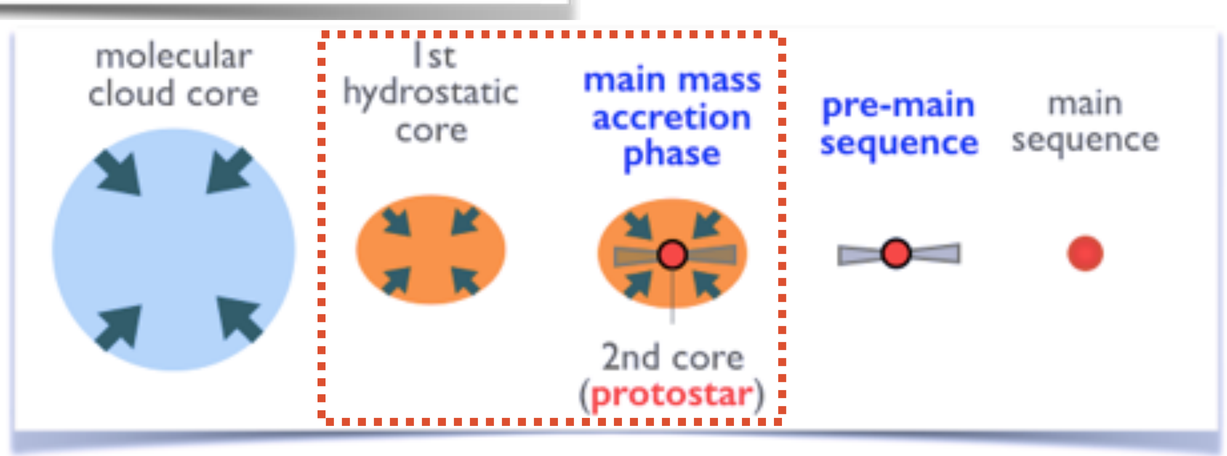
Basic physics of star formation



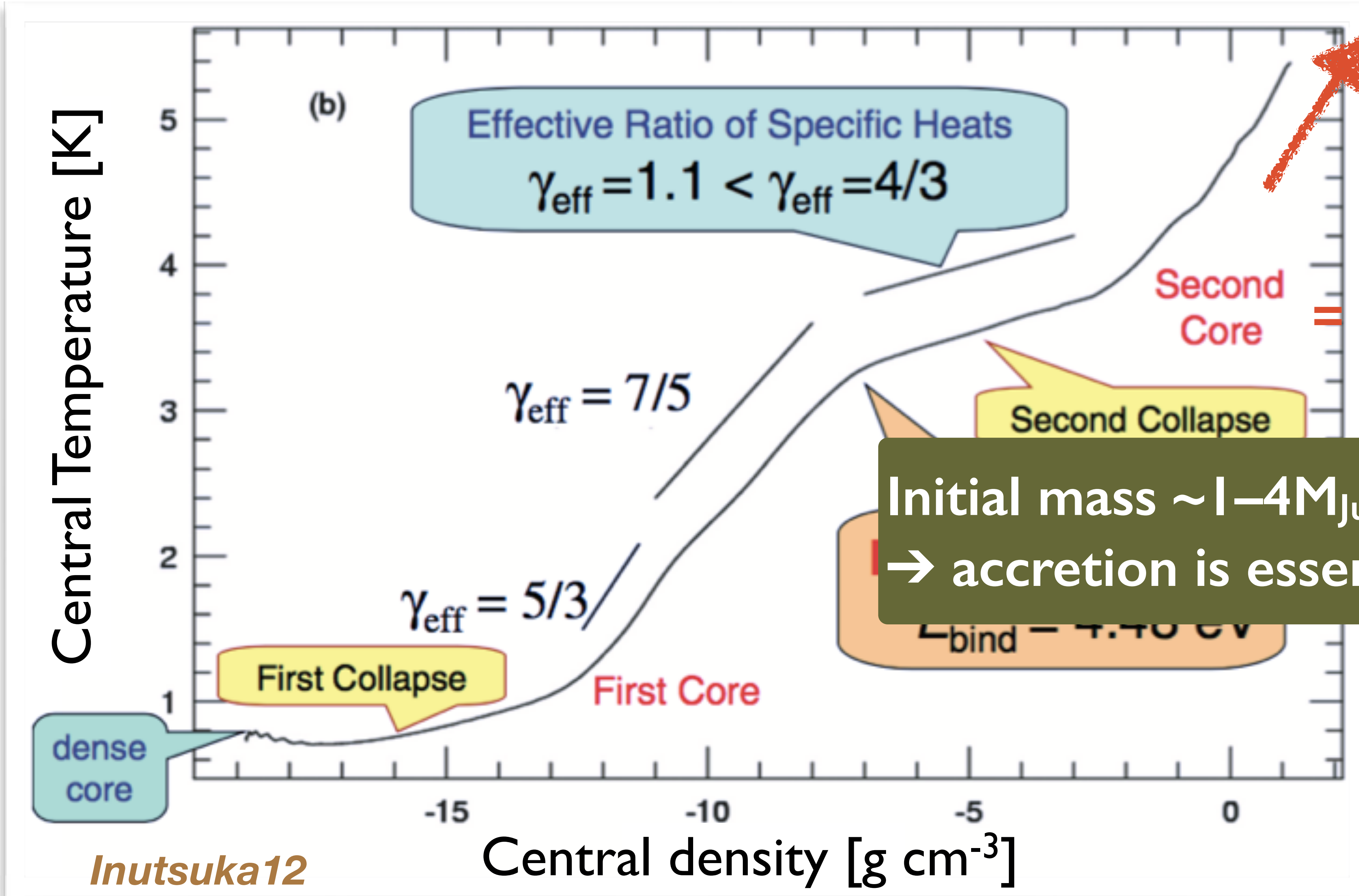
Dissociation is completed

➔ Formation of "2nd hydrostatic core"

= protostar



Basic physics of star formation



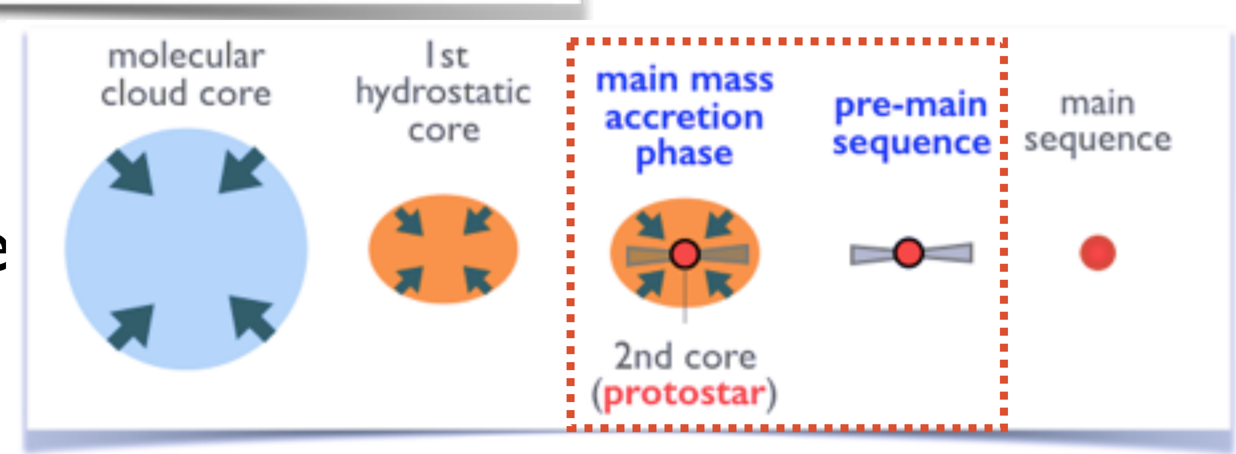
accretion continues
($\dot{M}$ ~ $10^{-5} M_\odot$/yr)

= "protostar"

Initial mass ~1–4M_{Jup} (=$10^{-3} M_\odot$)
→ accretion is essentially important

Masunaga+Inutsuka00, Vaytet+17

Dissociation is completed
→ Formation of "2nd hydrostatic core
= protostar



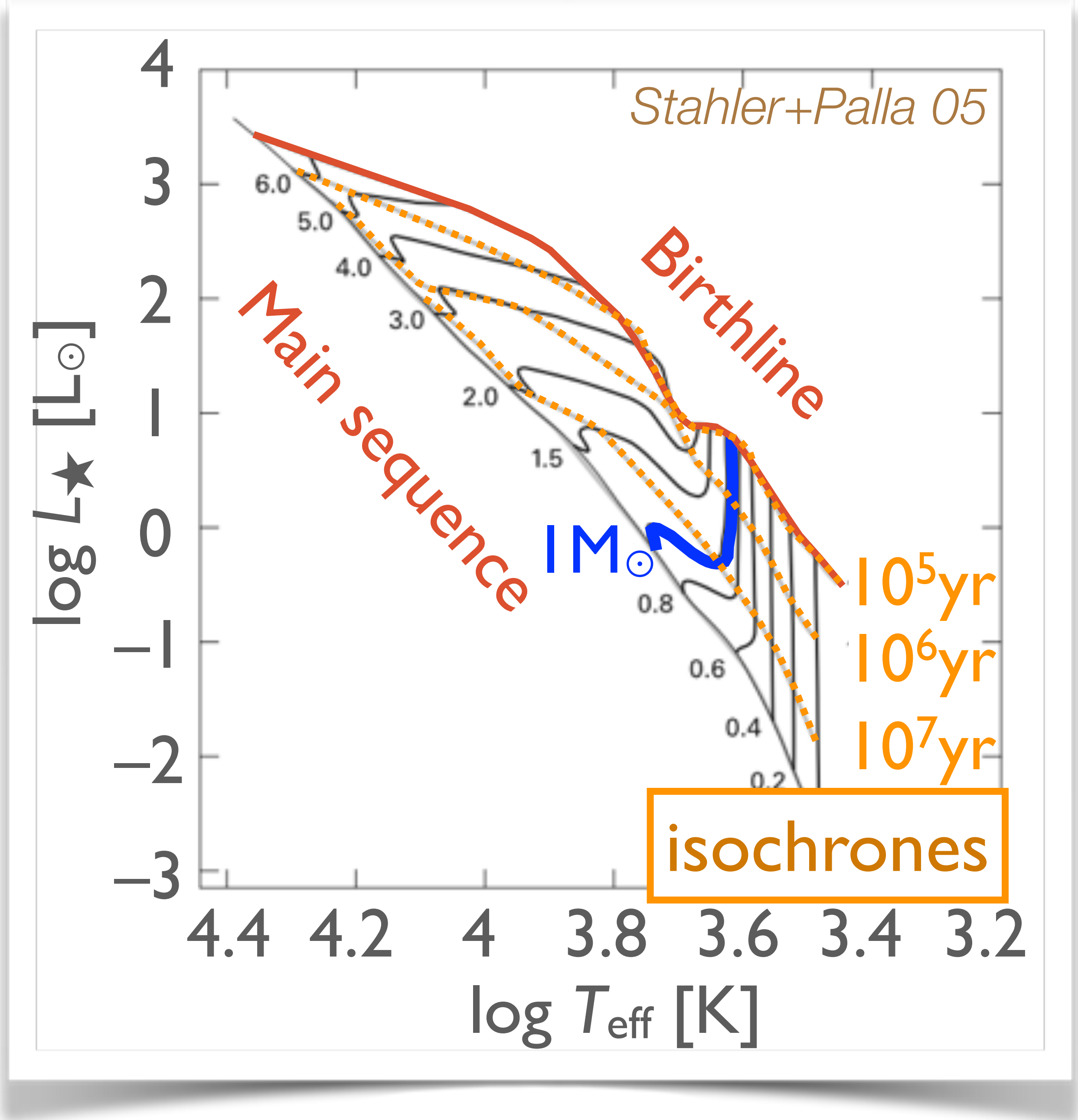
Standard picture of pre-MS evolution

- Stars are formed with large radius/luminosity
- Shrink along the Hayashi and Henyey tracks

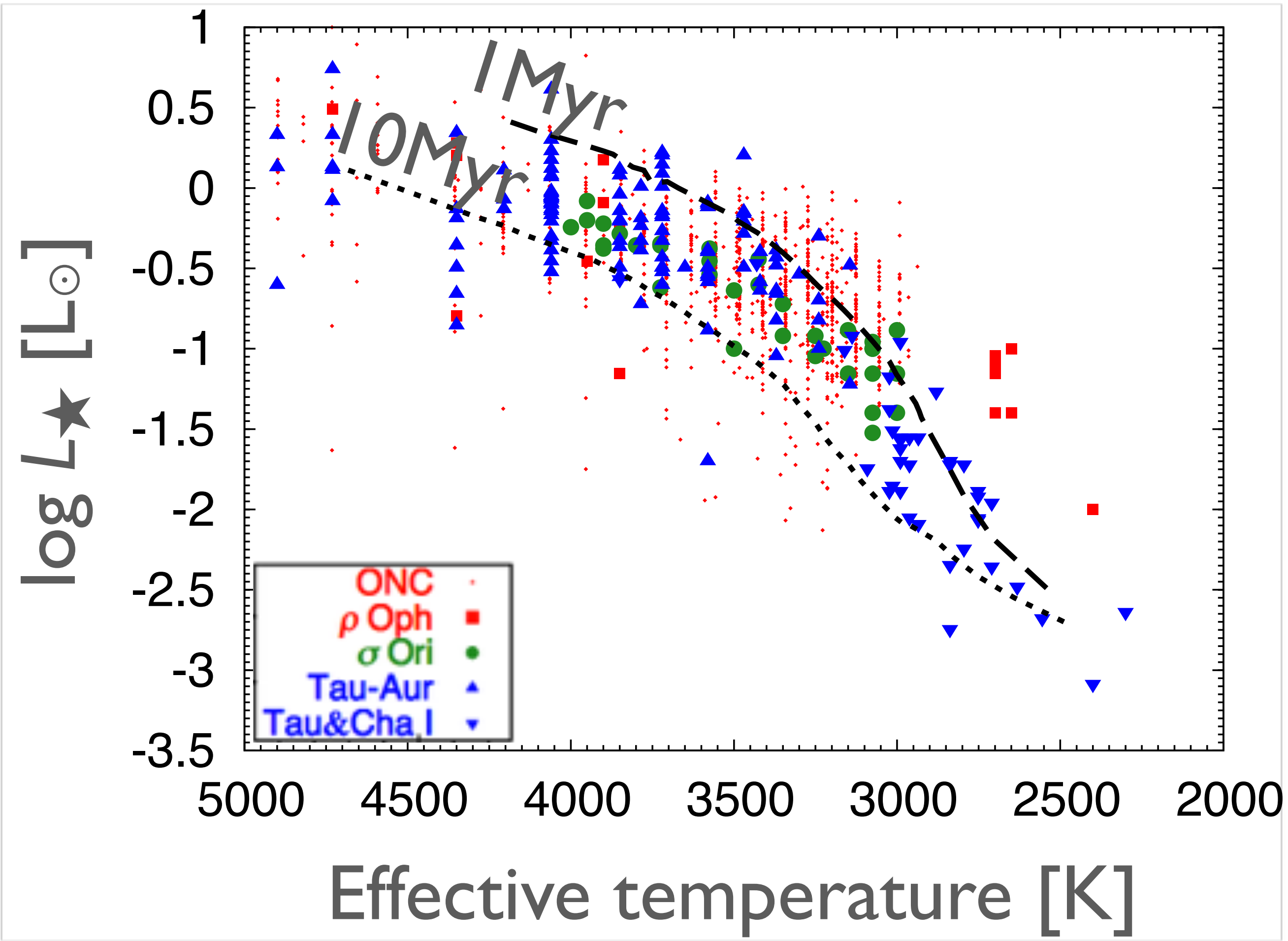
Stellar mass and age are estimated with evolutionary tracks

Understanding of pre-MS evolution is important!

Pre-MS evolutionary tracks in the H-R diagram



Luminosity spreads of pre-MS stars



- Luminosities of pre-MS stars spread widely (~1dex) *even in the same cluster*
- *If the classical isochrones are assumed,* the luminosity spreads correspond to ***age spreads*** (~10Myr)

Baraffe+98
Muzerolle+05, Da Rio+10,
Kenyon+Hartmann95,
Gatti+06,08
Hillenbrand09
Palla+Stahler00, Inutsuka+15
Baraffe+09, Hosokawa+11
Hartmann01

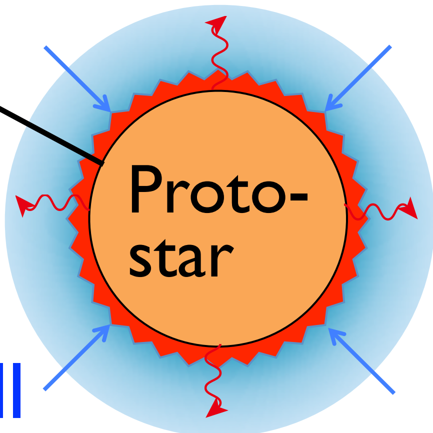
Possible solutions:

✓ Age spreads are genuine
✓ *Classical isochrones are inaccurate*
✓ Observational errors

Entropy of accreting materials

Standard PMS evolution is based on
Spherical accretion

Shock front



Free fall

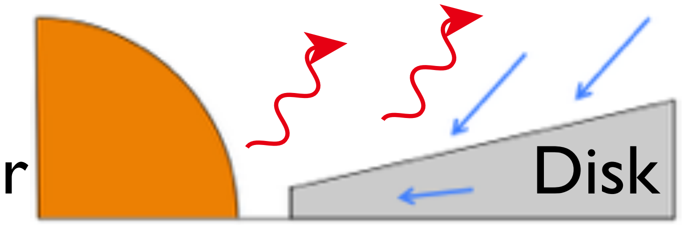
Inefficient radiative cooling
➔ **Efficient entropy injection to the star**

e.g., Stahler+80, Masunaga+Inutsuka00

Recent simulations suggest
Disk accretion

Radiative cooling

Protostar



Efficient radiative cooling from disk's and stellar surface
➔ ***Low-entropy accretion***

e.g., Baraffe+09,10,12, Hosokawa+11, Vorobyov+17

Aim of this study:
We revisit pre-MS evolution considering low-entropy accretion and discuss its impact on the observational problem

Method: Basic equations

- **Stellar structure equations (1D)** M_r: mass coordinate

1. **Continuity** $$\frac{\partial r}{\partial M_r} = \frac{1}{4\pi r^2 \rho}$$

Deuterium burning

2. **Momentum** $$\frac{\partial P}{\partial M_r} = -\frac{G M_r}{4\pi r^4}$$ (hydrostatic equilibrium)

3. **Energy** $$\frac{\partial l}{\partial M_r} = \varepsilon_{\rm nuc} - T\frac{\partial s}{\partial t} + \varepsilon_{\rm add}$$

entropy injection by accretion

4. **Temp. gradient** $$\frac{\partial T}{\partial M_r} = -\frac{G M_r T}{4\pi r^4 P}\nabla$$ $$\nabla = \frac{\mathrm{d}\ln T}{\mathrm{d}\ln P}$$

mixing-length theory, $\alpha_{\rm MLT}=1.905$

5. **Composition** $$\left(\frac{\partial X_i}{\partial t}\right)_{M_r} = \underbrace{\frac{m_i}{\rho}\left(\sum_j r'_{ji} - \sum_k r'_{ik}\right)}_{\text{nuclear reaction}} + \underbrace{\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 D \frac{\partial X_i}{\partial r}\right)}_{\text{diffusion}}$$

(Cox & Giuli68; Henyey+65)

- **Stellar evolution code** MESA *Paxton+11,13,15*

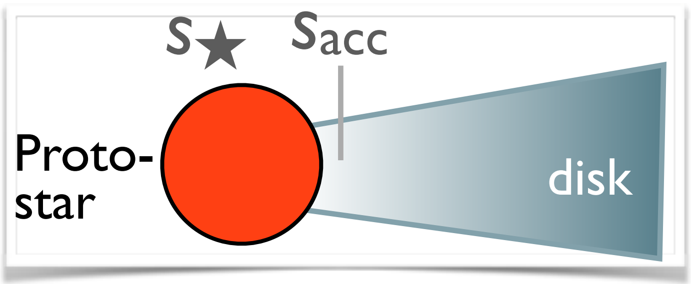
Method: Heat injection by accretion

Energy Eq.

$$\frac{\partial l}{\partial M_r} = \varepsilon_{\rm nuc} - T\frac{\partial s}{\partial t} + \varepsilon_{\rm add}$$

entropy injection by accretion

(s: entropy)



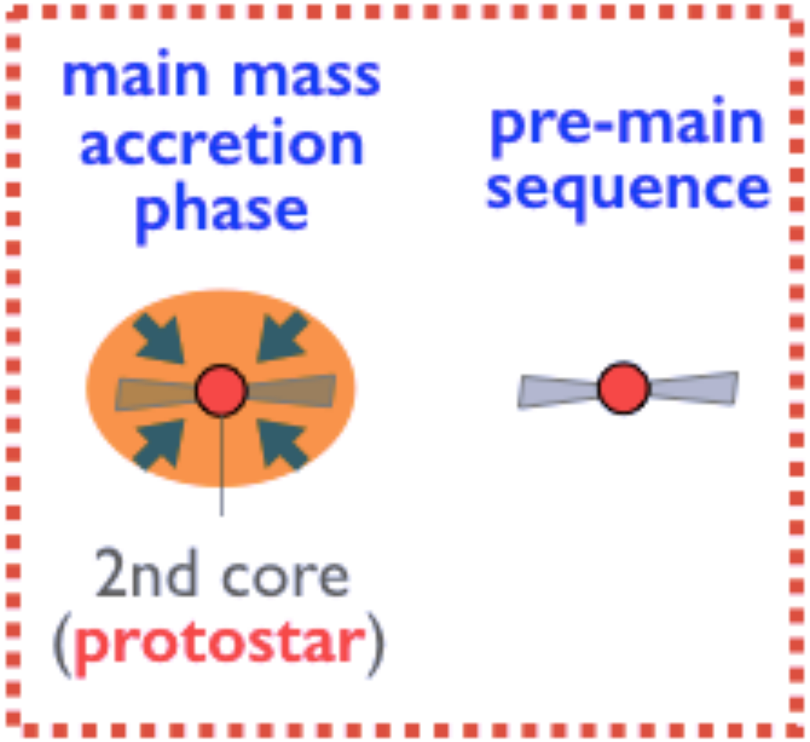
$$\boxed{\varepsilon_{\rm add} = \xi\, L_{\rm acc}/M_\star} \quad L_{\rm acc} = GM_\star \dot{M}/R_\star$$

We assume that a fraction of the gravitational energy of accreting materials is injected

In total, injected energy $L_{\rm add} = \xi L_{\rm acc}$

Method: Fiducial settings

- Accretion: $0.01\mathrm{M}_\odot \rightarrow \dot{M}=10^{-5}\mathrm{M}_\odot/\mathrm{yr} \rightarrow 1\mathrm{M}_\odot$
- Heat injection: $\boldsymbol{\xi}$**=0–0.5**
- Initial radius: $\boldsymbol{R_{\mathrm{ini}}=1.5\mathrm{R}_\odot}$
- Composition: Z=0.02, *Deuterium content* $\boldsymbol{X_\mathrm{D}}$ **= 20 ppm** (2×10^{-5})

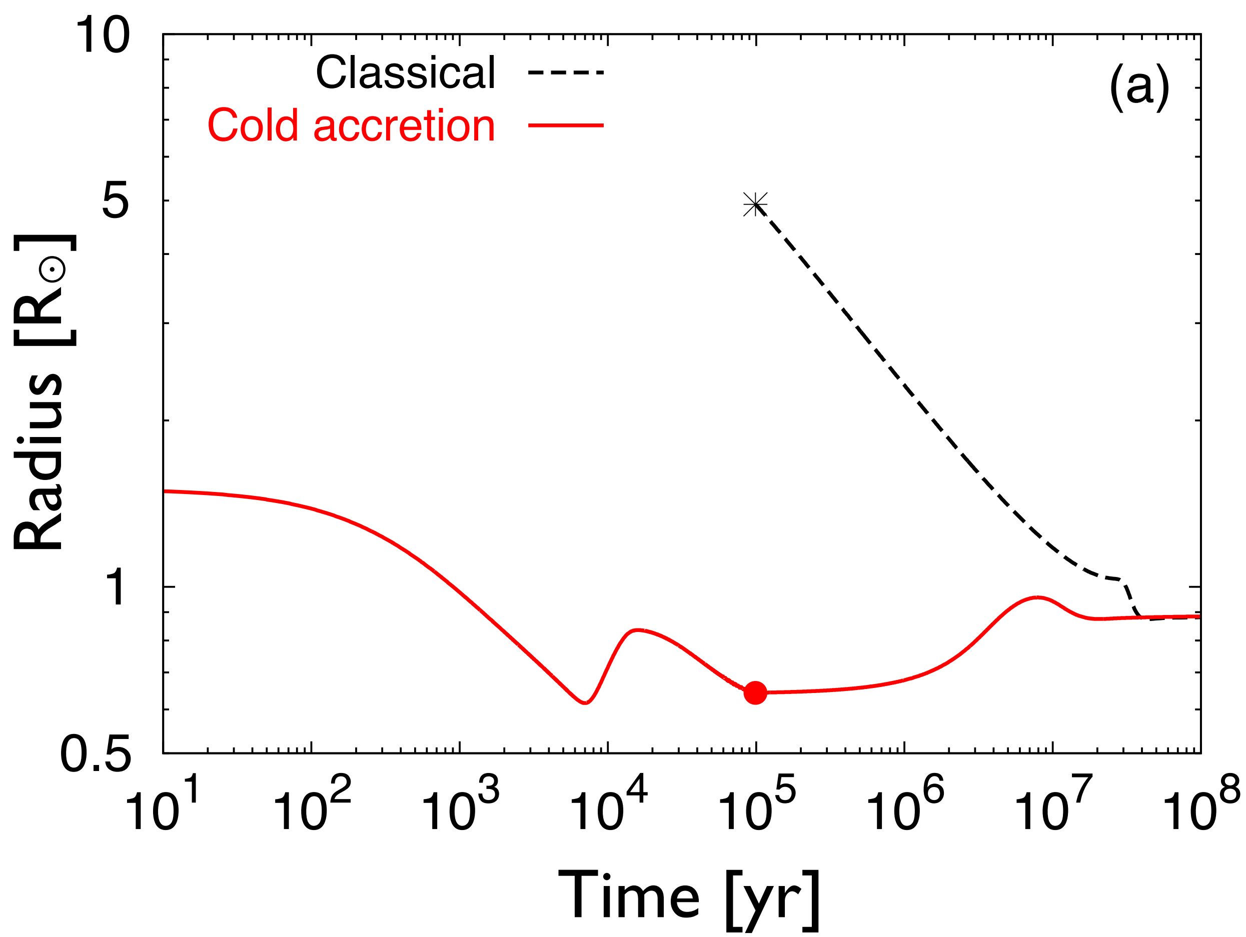


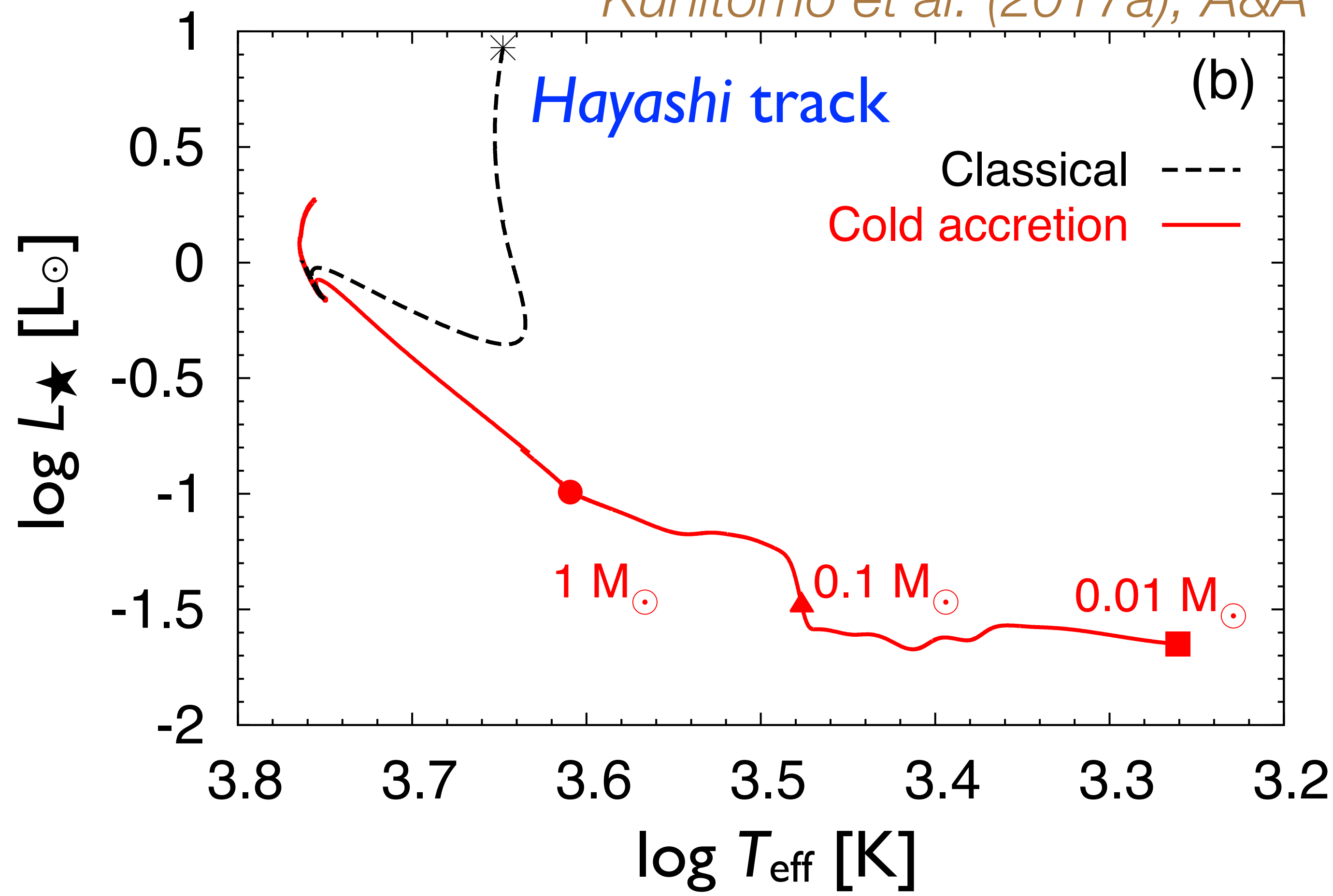
Results:

Pre-MS evolutions with various accretion heating, ξ

PMS evolution with low-entropy accretion

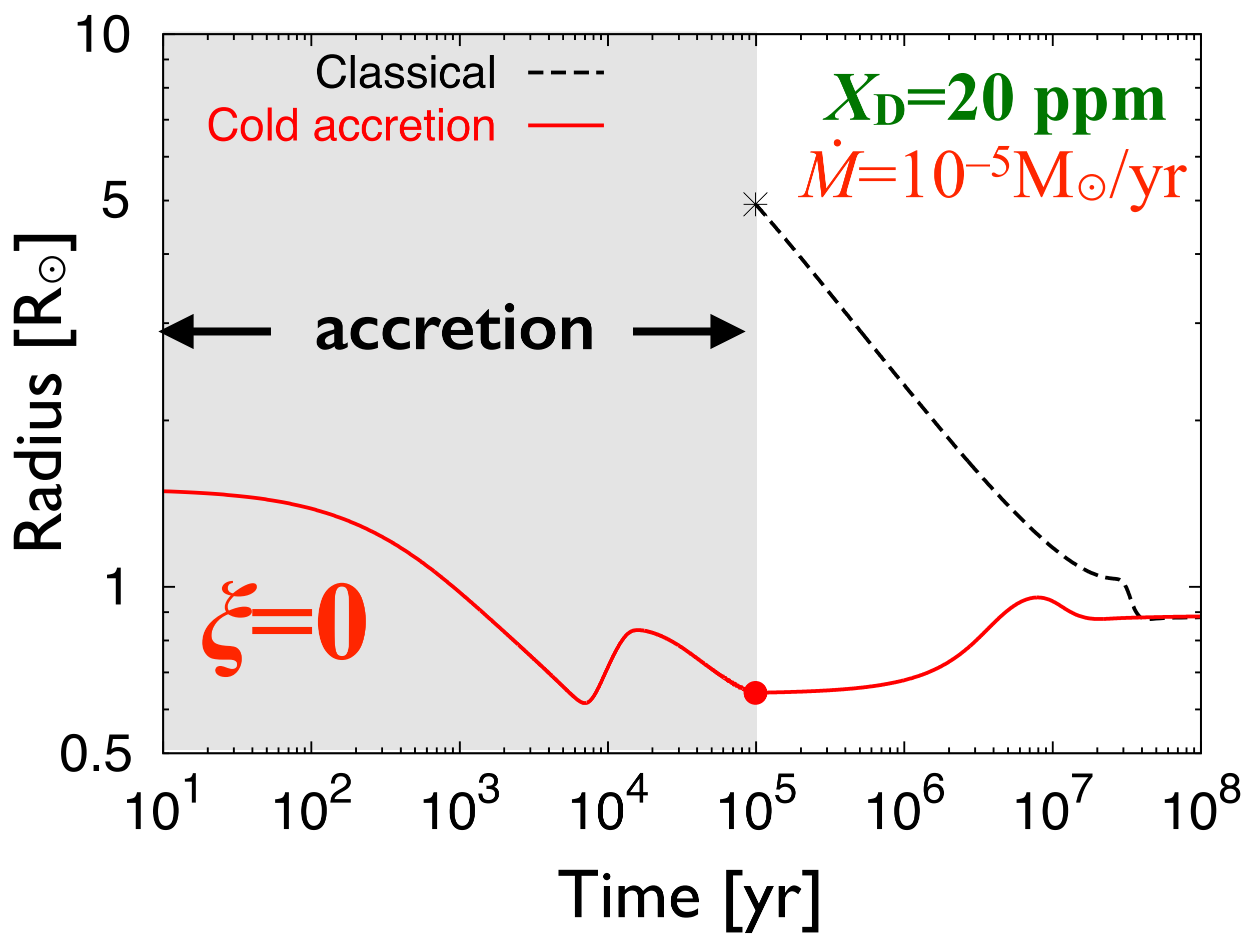
Kunitomo et al. (2017a), A&A



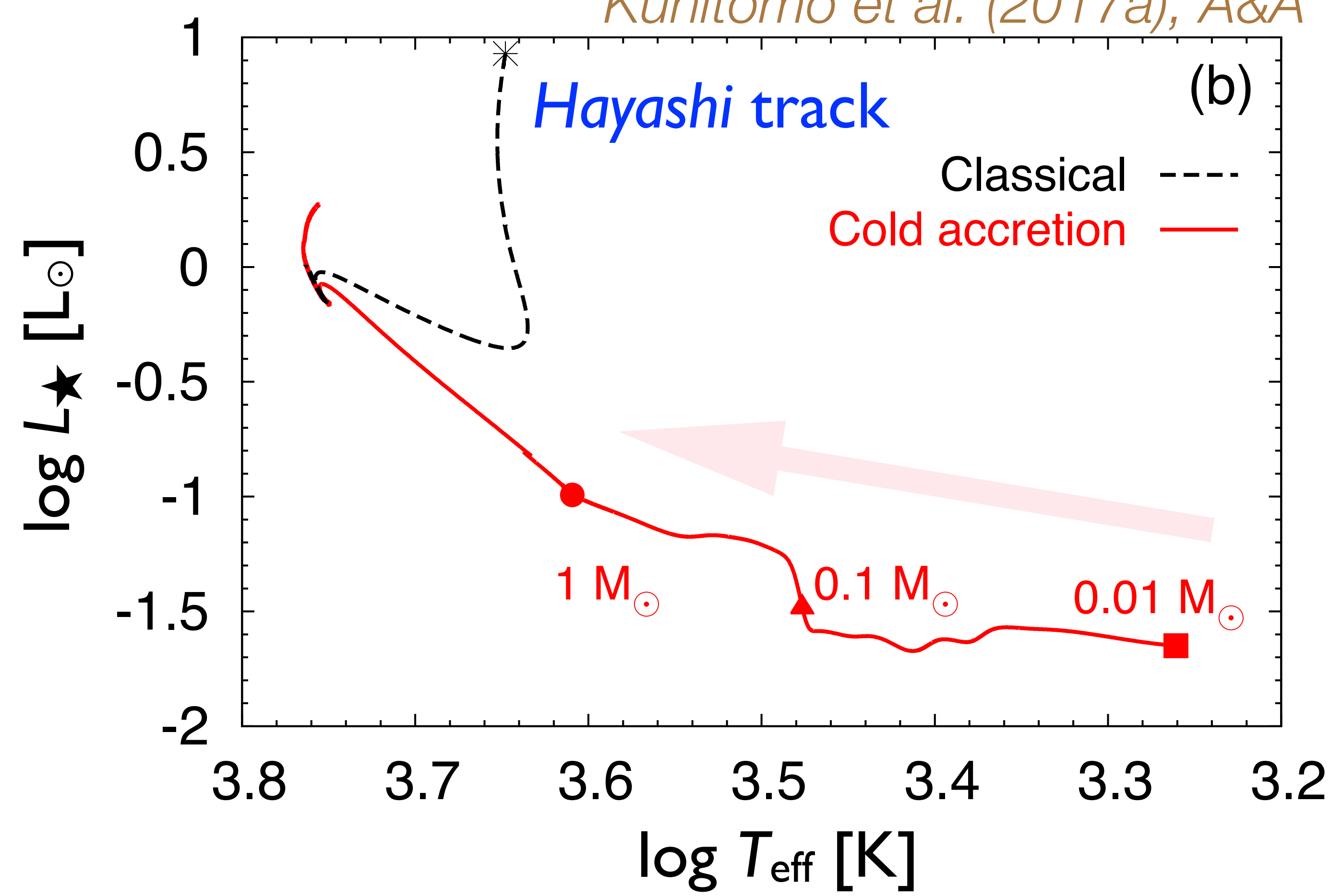


Standard evolution of 1M⊙ stars:
Stars are formed with a large radius and luminosity

PMS evolution with low-entropy accretion



Kunitomo et al. (2017a), A&A



Pre-MS evolution with *low-entropy accretion* is totally different from the standard one

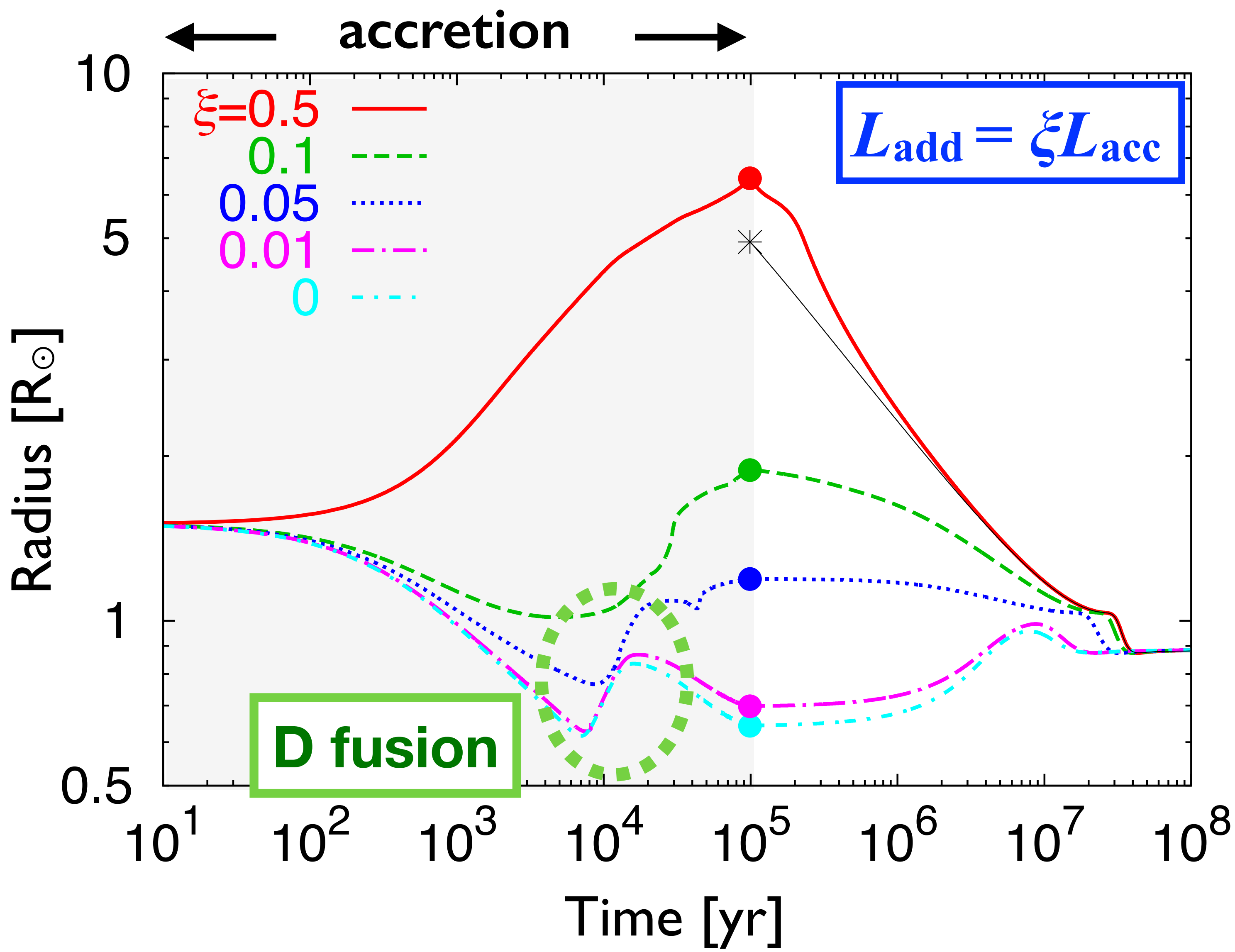
- Radius: ~10 times smaller
- Luminosity: ~100 times smaller

Baraffe+09,10,12, *Hosokawa+11*

Dependence on heat injection efficiency ξ

Kunitomo et al. (2017a), A&A

Pre-MS evolution is controlled by ***heat injection*** and ***deuterium fusion***



Deuterium fusion is a strong exothermic reaction

$$\mathrm{D} + {}^{1}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + 5.5\,\mathrm{MeV}$$

➔ entropy generation
➔ stars expand

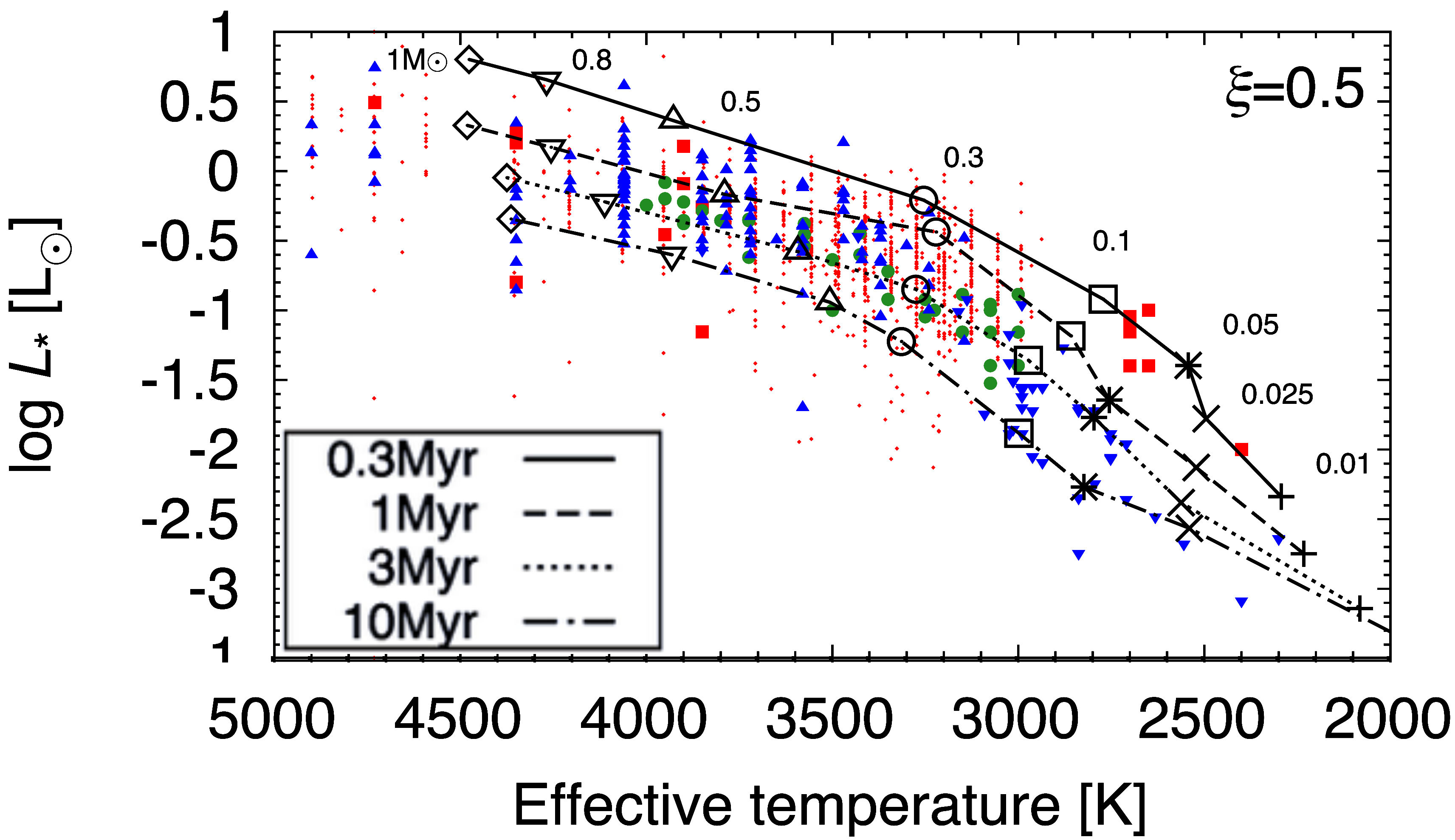
Radius can be different by up to a factor of 10 (ξ)

Impact on luminosity spread problem

▪ Fixed ξ value

$L_{add} = \xi\, GM\dot{M}/R$

Kunitomo et al. (2017a), A&A



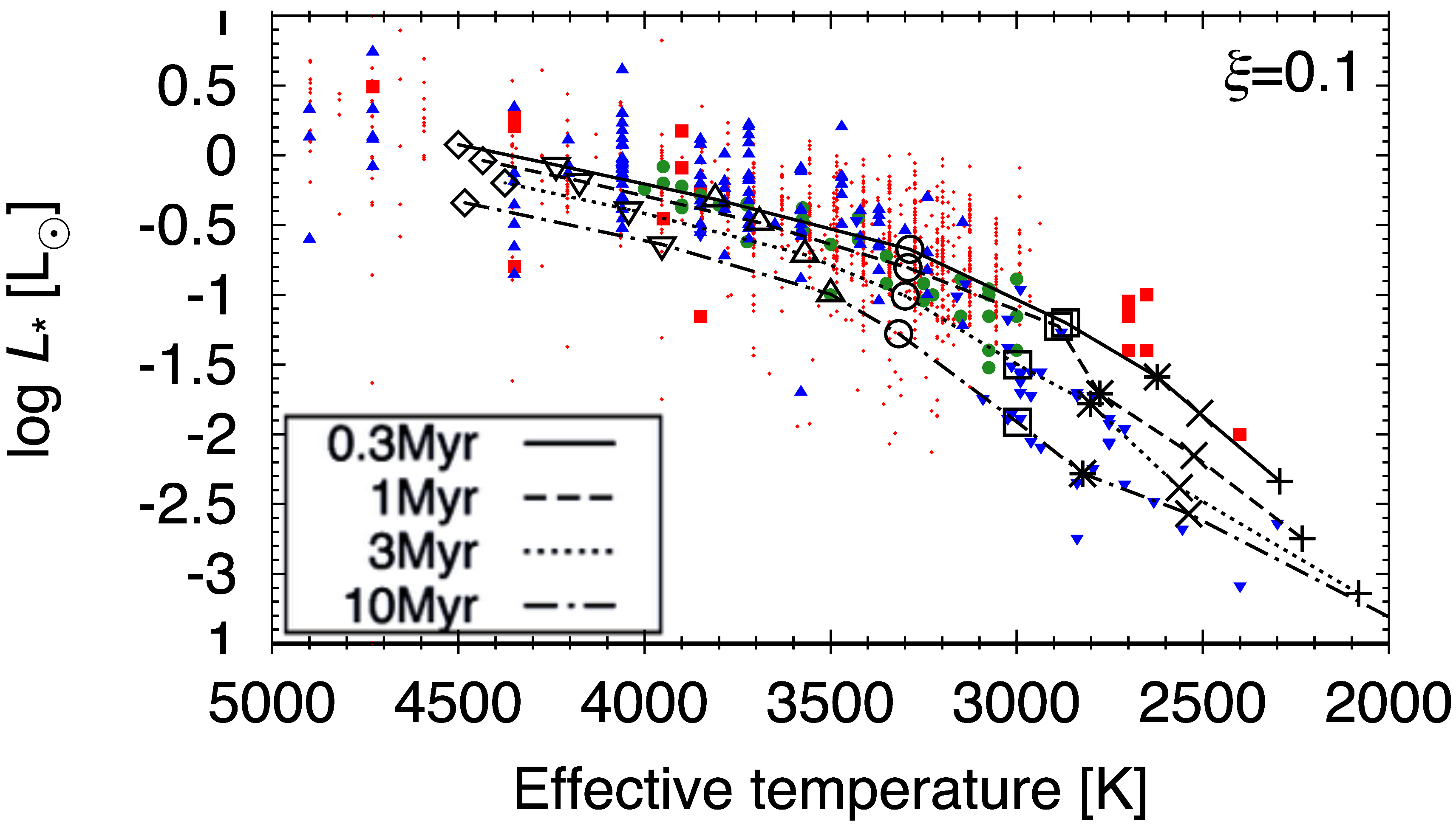
The luminosity spreads can be explained with large age spreads

Impact on luminosity spread problem

- **Fixed ξ value**

$L_{\mathrm{add}} = \xi\, GM\dot{M}/R$

Kunitomo et al. (2017a), A&A

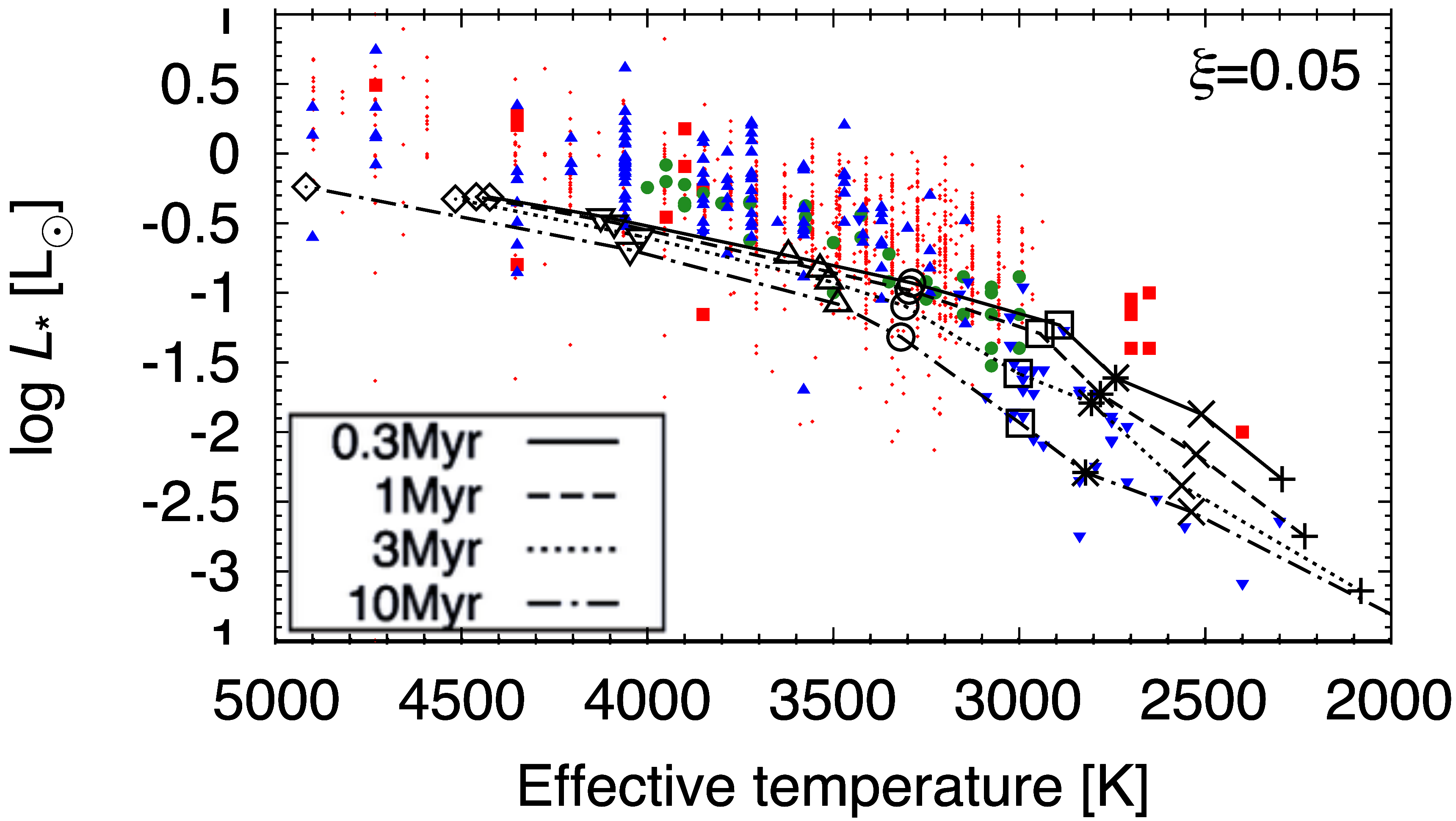


the most luminous stars cannot be explained anymore

Impact on luminosity spread problem

Kunitomo et al. (2017a), A&A

- **Fixed ξ value** $\boxed{L_{\rm add} = \xi\, GM\dot{M}/R}$

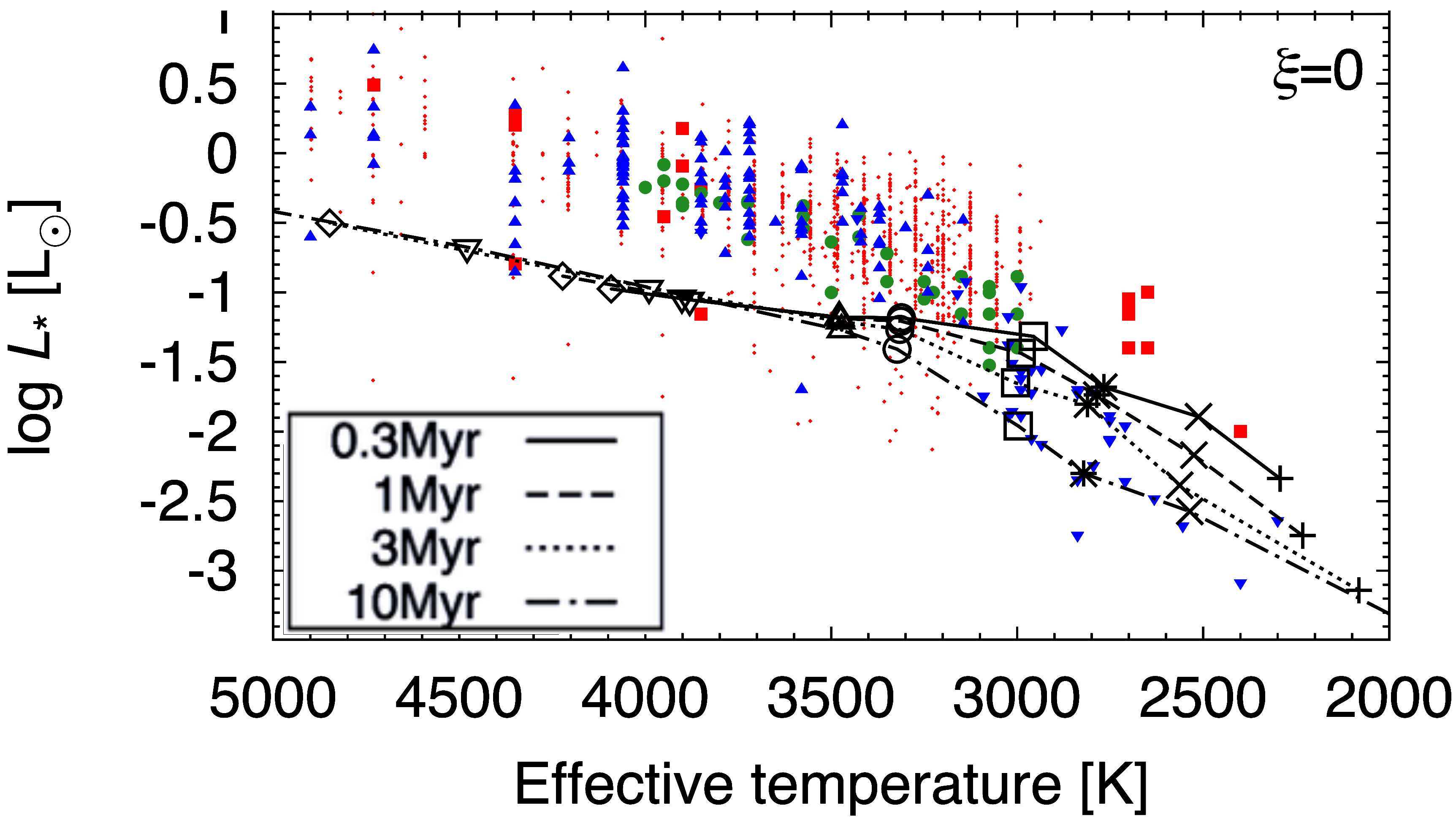


the slope of the isochrones becomes inconsistent with the ensemble of observational data points

Impact on luminosity spread problem

- **Fixed ξ value** $\boxed{L_{\rm add} = \xi\, GM\dot{M}/R}$

Kunitomo et al. (2017a), A&A

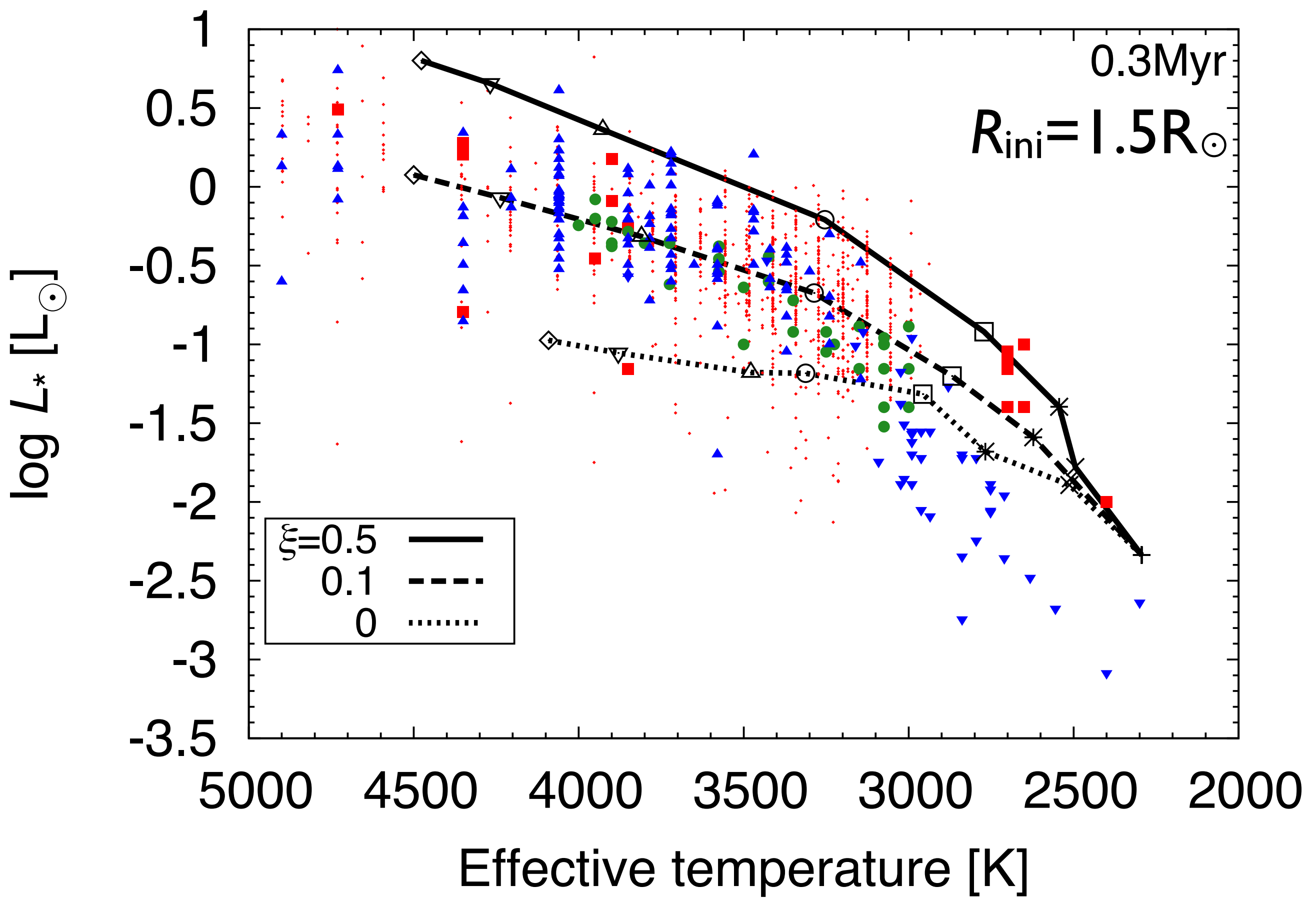


the slope of the isochrones becomes inconsistent with the ensemble of observational data points

Impact on luminosity spread problem

▪ Variable ξ value with fixed age

Kunitomo et al. (2017a), A&A



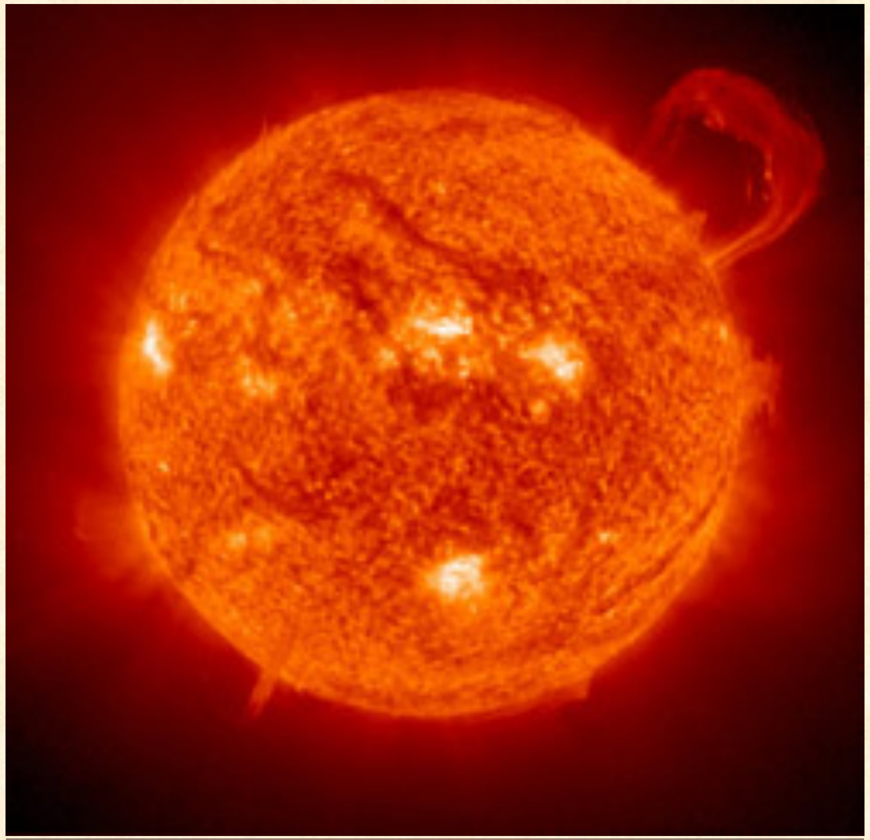
Different ξ values can create luminosity spreads *without invoking age spreads*

Baraffe+09, 12

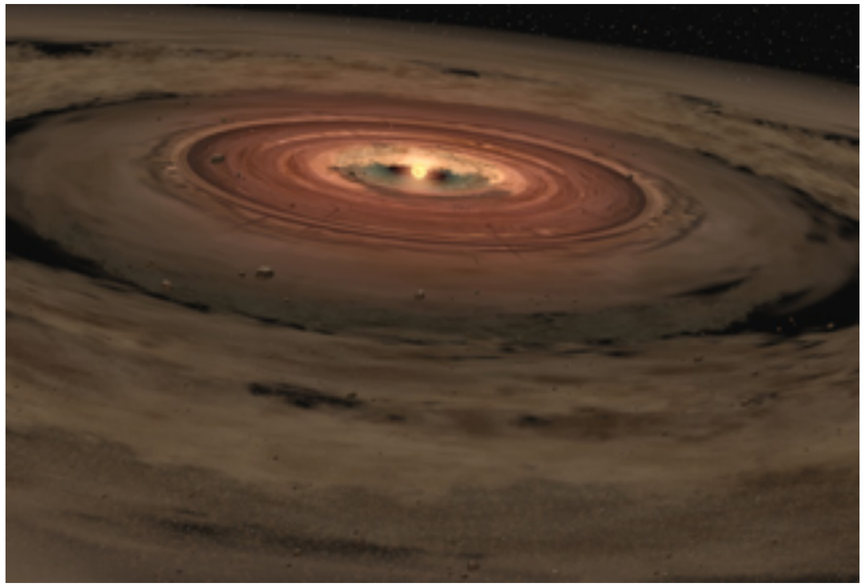
We suggest most (~90%) stars have been formed with $\xi \gtrsim 0.1$

because the number of underluminous stars is small

Part 2: Consequences of low-entropy accretion on stellar surface composition

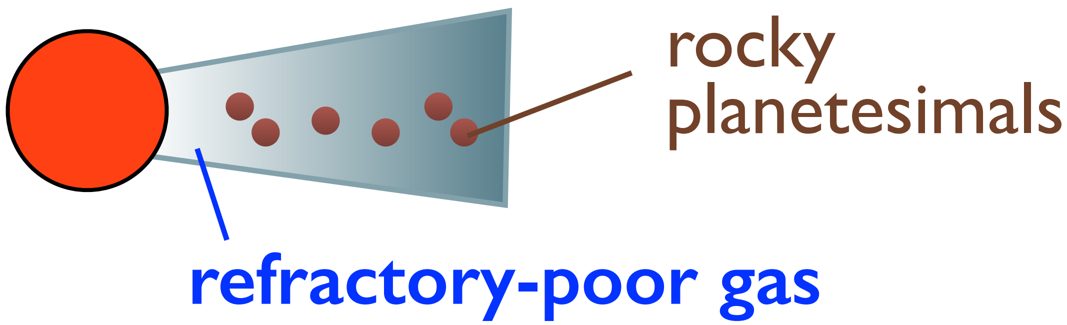


Composition of protoplanetary disks



- Planets are formed in protoplanetary disks
- Composition of disks:
  - mainly H_2 and He gas
  - refractory elements (~0.4%)
    (e.g., Fe, Mg, Si, etc.) *Asplund+09*

- Planet formation can change the disk composition
- Disk gas accretes onto the host star

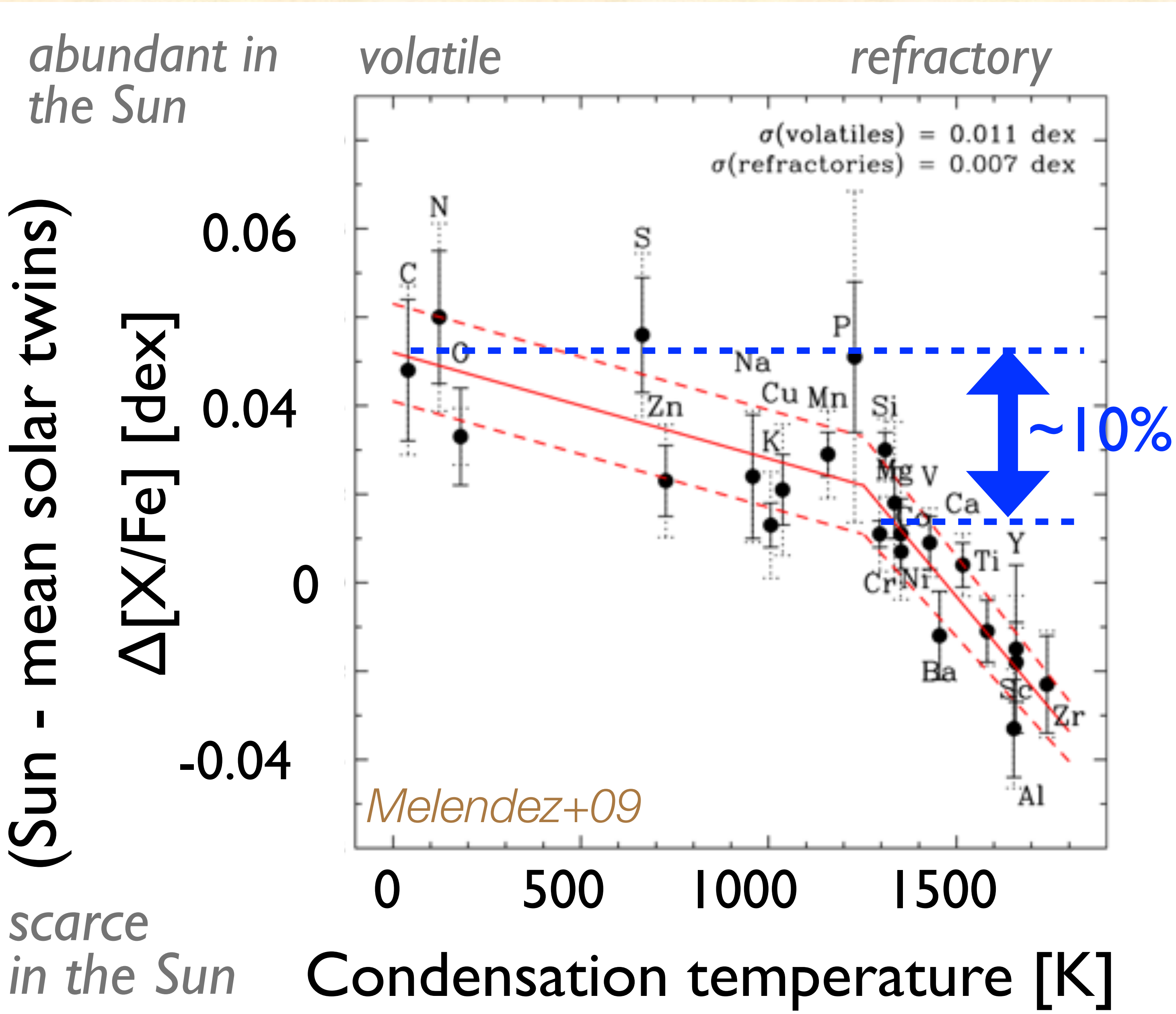


Does planet formation* pollute *stellar surface composition?

(=change from a primordial one)

Possible observational signatures of pollution

Solar composition anomaly



- the Sun has the **refractory-poor** composition compared to most solar twins
  - **~15%** solar-twins also have the solar-like composition
- difference: ~10%

e.g., Melendez+09, Ramirez+09

<u>Possible scenarios:</u>

✓Pollution?

✓Migration of the solar system in the Galaxy?

Chambers10; Adibekyan+14

Possible observational signatures of pollution

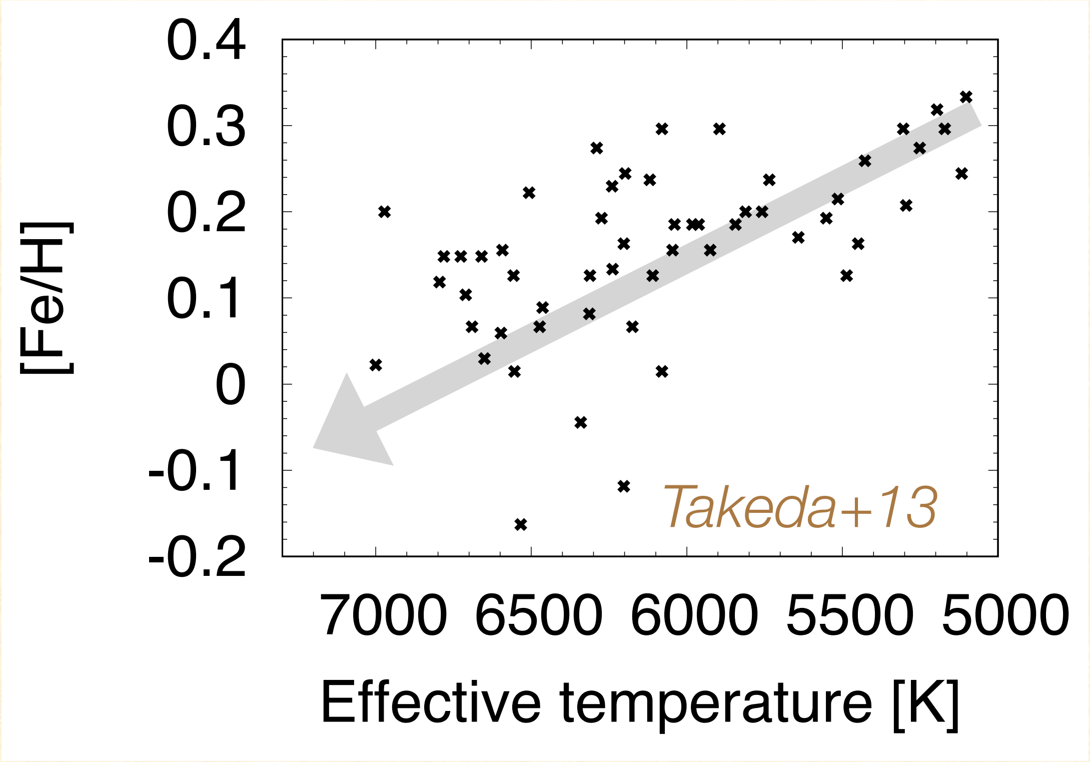
Binary systems (16 Cyg, XO-2)

Ramirez+11; Damasso+15

The surface composition of *planet harboring stars* is metal-poor compared to the other star

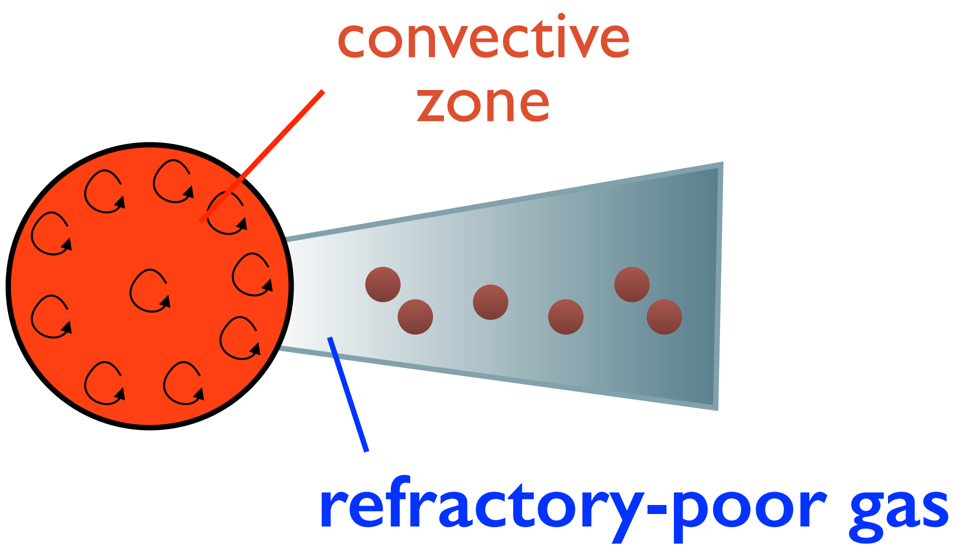
Metallicity gradient of Hyades cluster

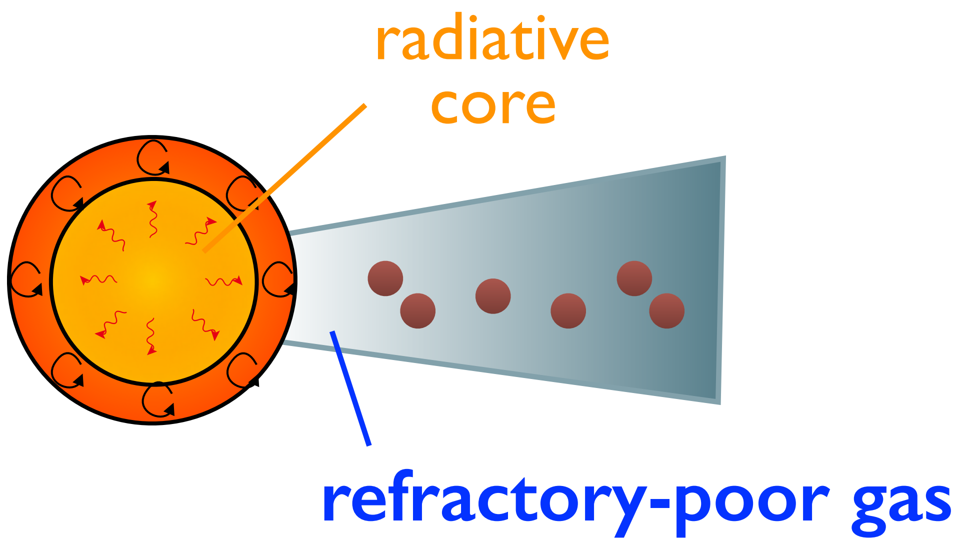
In Hyades cluster, higher-mass stars have lower metallicity
➔ stronger impact of planet formation on higher-mass stars?



Internal structure of pre-MS stars

⚠️ *surface convective zone should be small before disk dispersal*



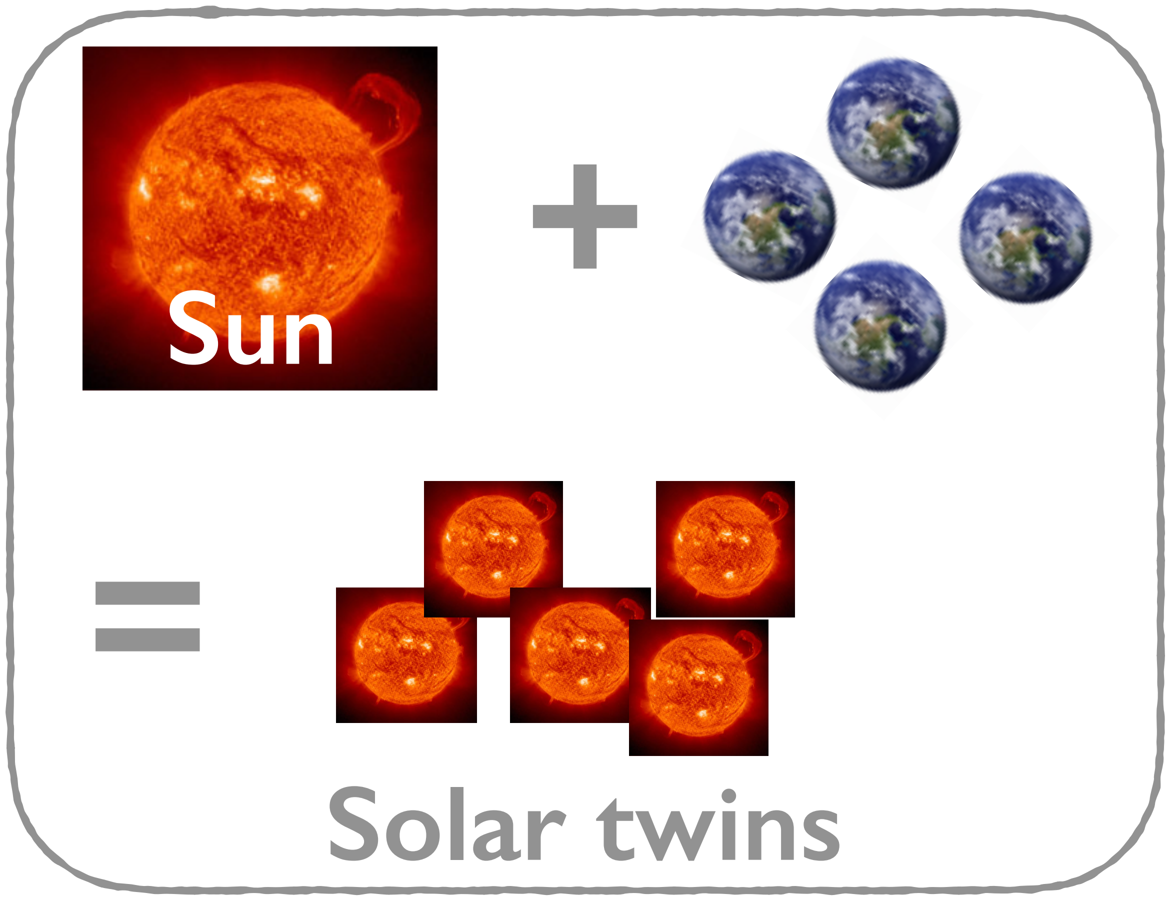


Fully convective stars
accreted gas is diluted
in the entire star
→ **pollution is limited**

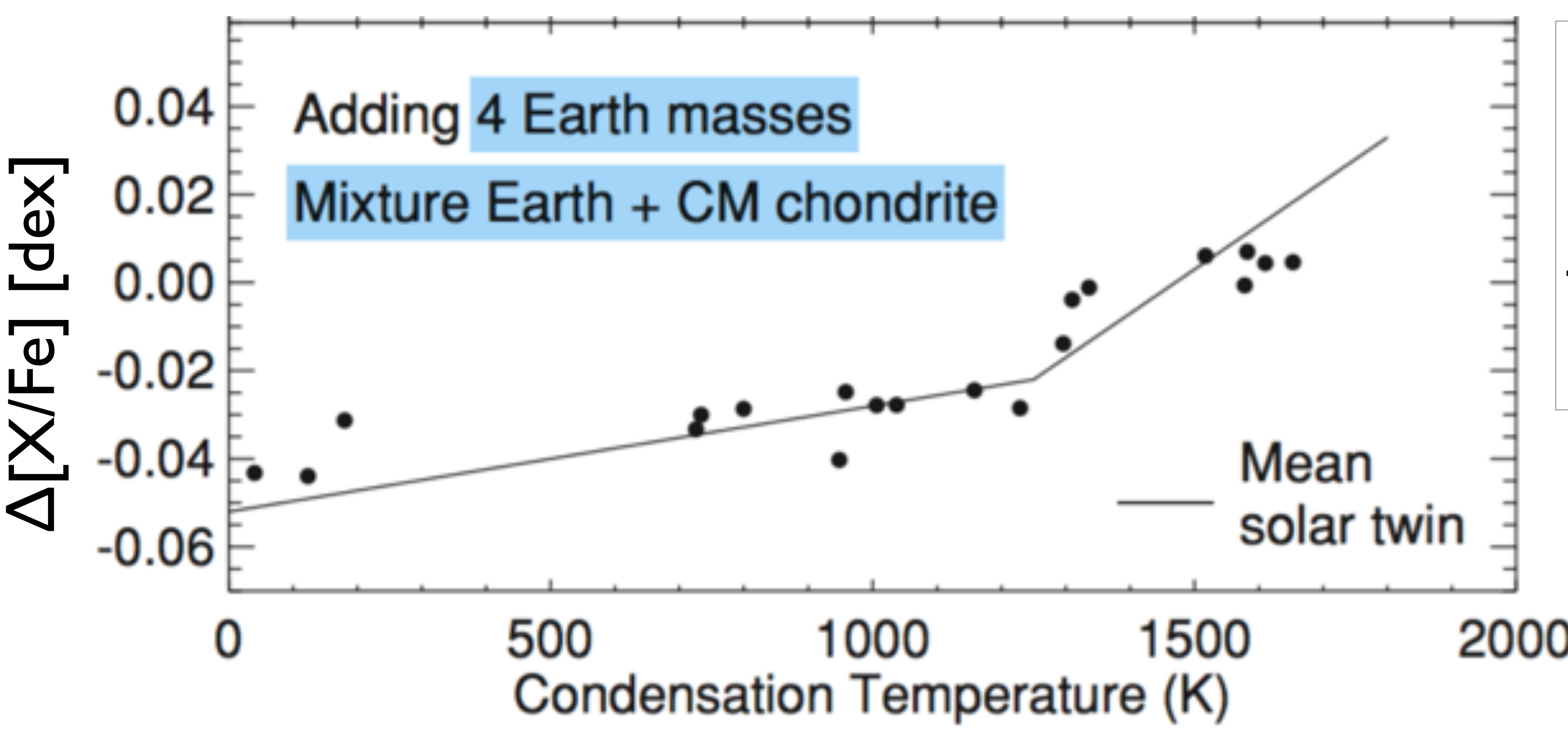
Stars with a large radiative core
accreted gas is distributed
only in the thin convective zone (CZ)
→ ***strong pollution!***

The thickness of surface convective zone is important

Previous study on solar anomaly: Chambers (2010)



Accretion of $4M_{\oplus}$ rocks makes the solar composition as refractory-rich as solar twins **using internal structure of the present-day Sun**



●: Adding $4M_{\oplus}$ rocks to solar surface CZ

—: Composition of solar twins

Internal structure of pre-MS stars

surface convective zone should be small before disk dispersal

→ pollution is limited

→ *strong pollution!*

Purpose of part 2:
Evaluating the consequences of planet formation with the up-to-date pre-MS evolution models

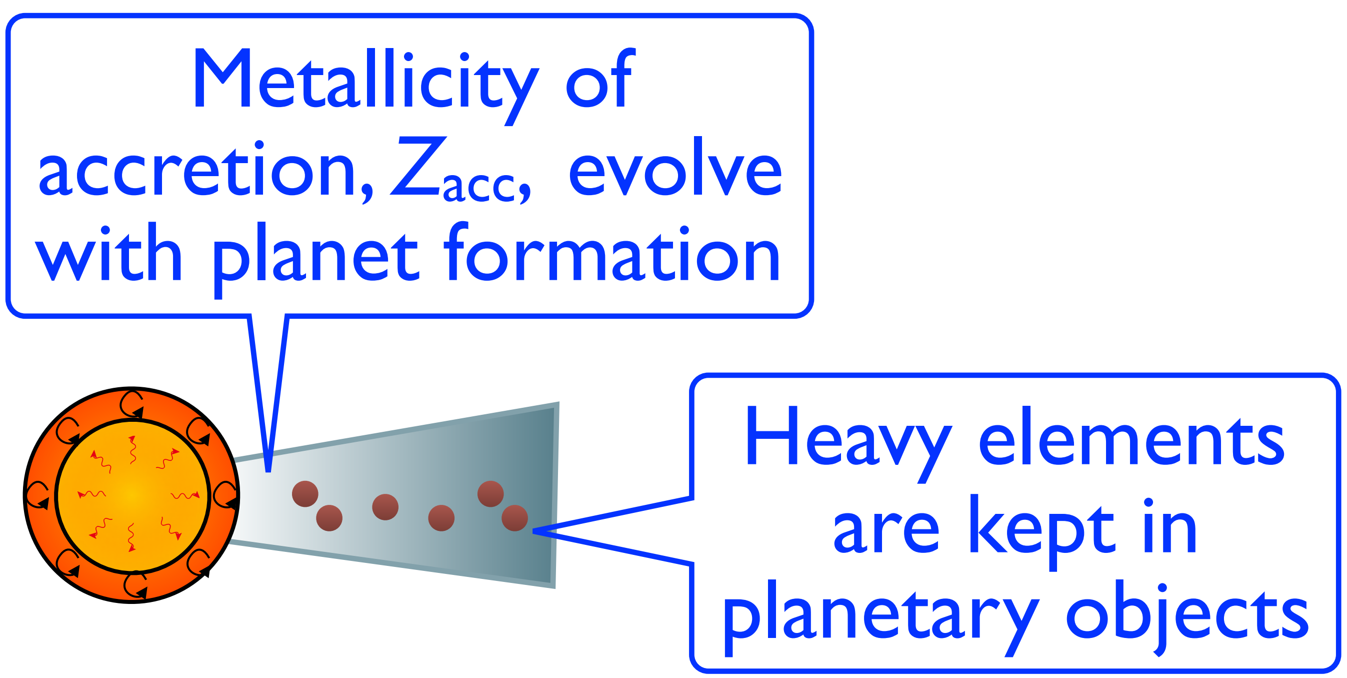
The thickness of surface convective zone is important

Determination of the magnitude of pollution

- The magnitude of pollution depends on stellar evolution and planet formation
  - Planet formation model:
    - Total solid mass in planets, M_{solid}
    - Ice-to-rock ratio, $f_{ice/rock}$
  - Accretion history: $\dot{M} \propto t^{-1.5}$ & disk lifetime~10Myr
  - Evolution of convective zone mass, M_{CZ}

Hartmann+98
Haisch+01

$$Z_{\rm surf} = \frac{M_{\rm CZ}\, Z_{\rm surf} + M_{\rm acc}\, Z_{\rm acc}}{M_{\rm CZ} + M_{\rm acc}}$$



Solids in planets in the solar system

- Total solid mass in planets, M_{solid}
  - Terrestrial planets: $2M_\oplus$
  - Jupiter+Saturn: $30\text{-}70M_\oplus$ *e.g., Guillot05, Miguel+16, Wahl+17, Helled+Guillot13*
  - Uranus+Neptune: $\sim 25\text{–}28M_\oplus$ *e.g., Nettlemann+13*
  - +Missing objects: $\sim 60\text{–}100M_\oplus$ *e.g., O'Brien+07, Tsiganis+05, Izidoro (private comm.)*

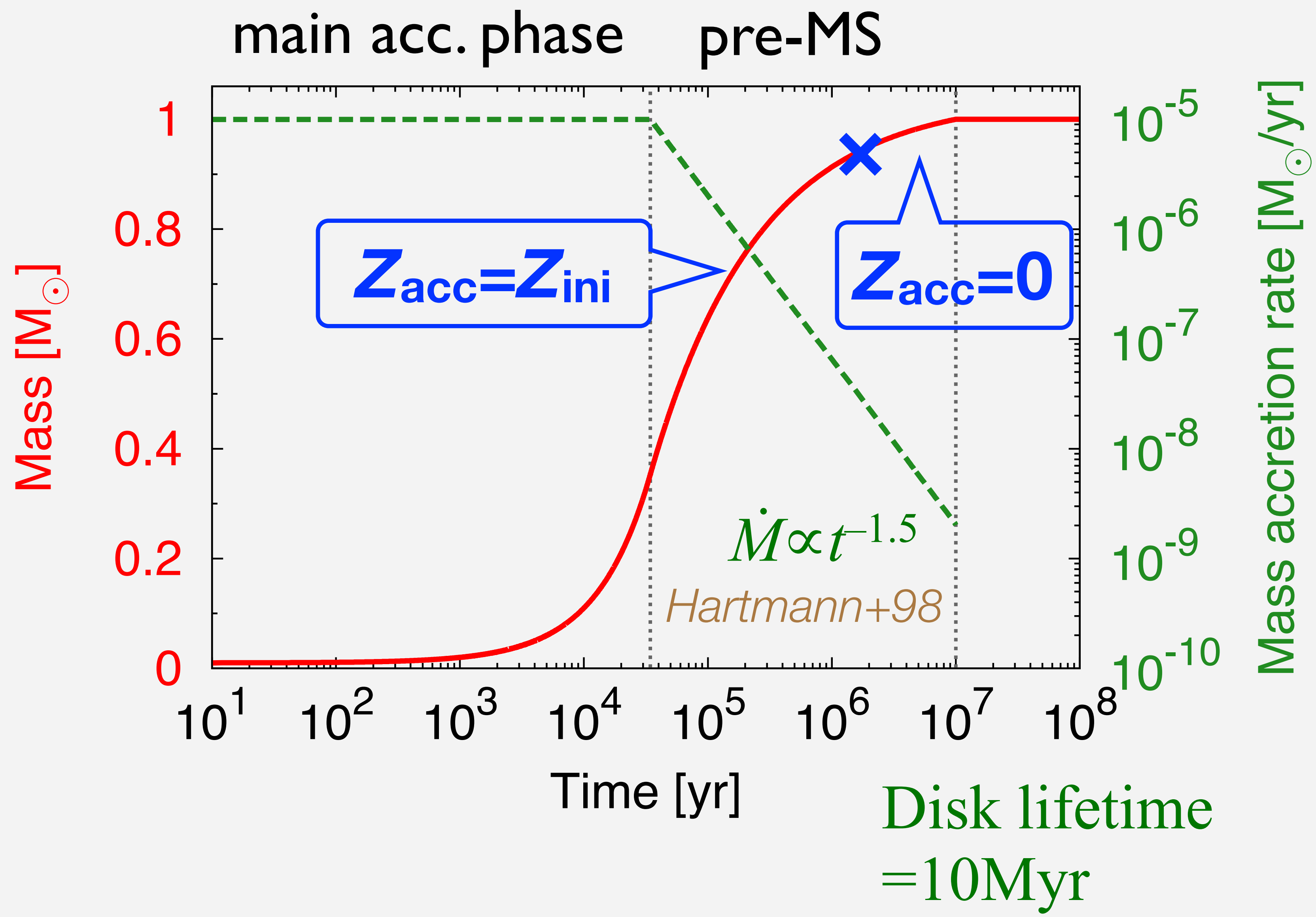
→ $\sim 150M_\oplus$ solids

→ $0.03M_\odot$ metal-free accretion ($150M_\oplus/Z_\odot$, $Z_\odot$=0.0134)

Asplund+09

- Ice-to-rock ratio, $f_{ice/rock}$
  - Solar photosphere = 2.0 *Lodders03*
    - Lower $f_{ice/rock}$ than 2.0 in planets induces refractory-poor accretion
  - Highly uncertain in giant planets

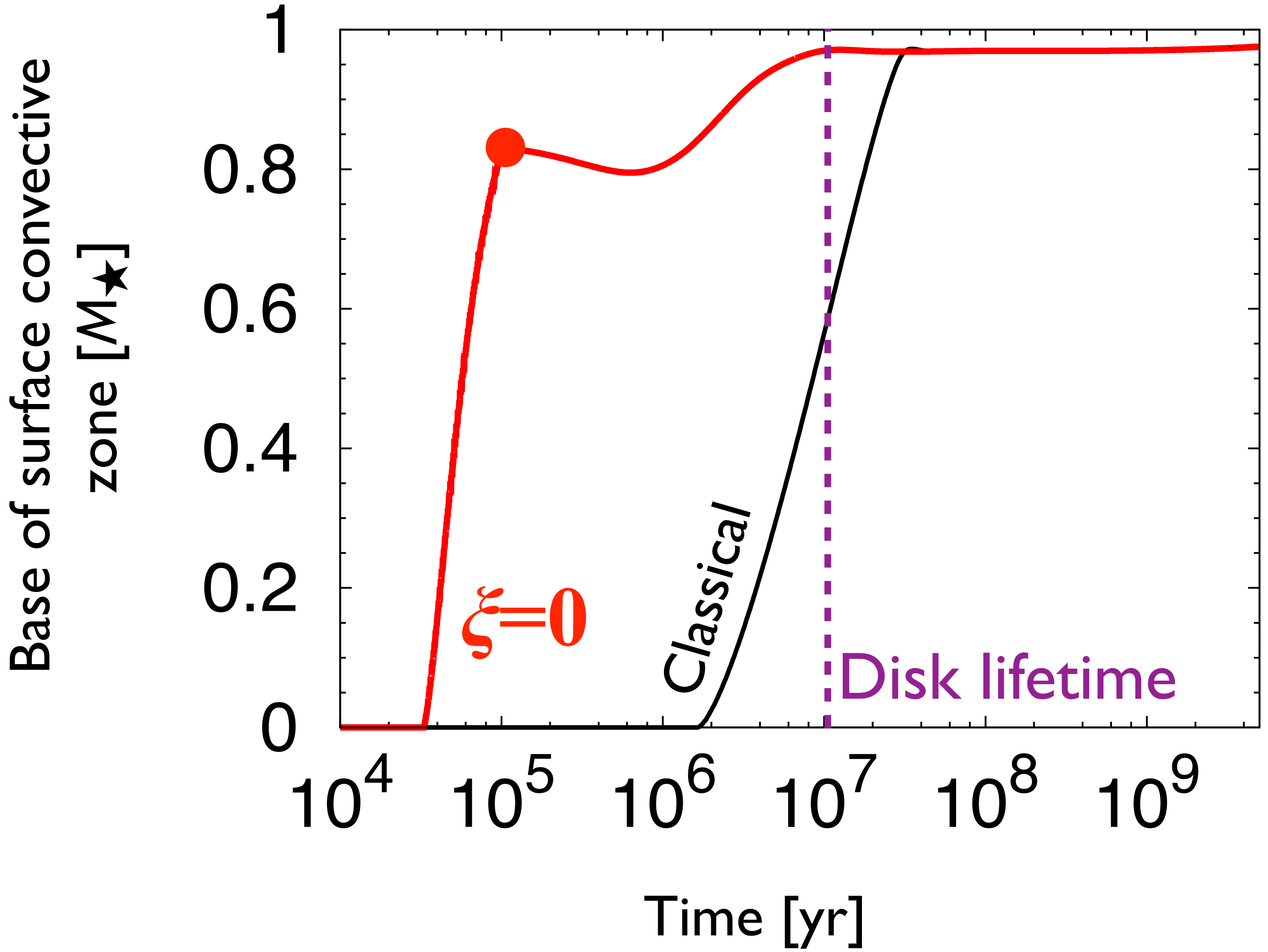
Accretion history



$$Z_{\rm surf} = \frac{M_{\rm CZ}\, Z_{\rm surf} + M_{\rm acc}\, Z_{\rm acc}}{M_{\rm CZ} + M_{\rm acc}}$$

Internal structure with low-entropy acc.

Kunitomo et al., in prep.



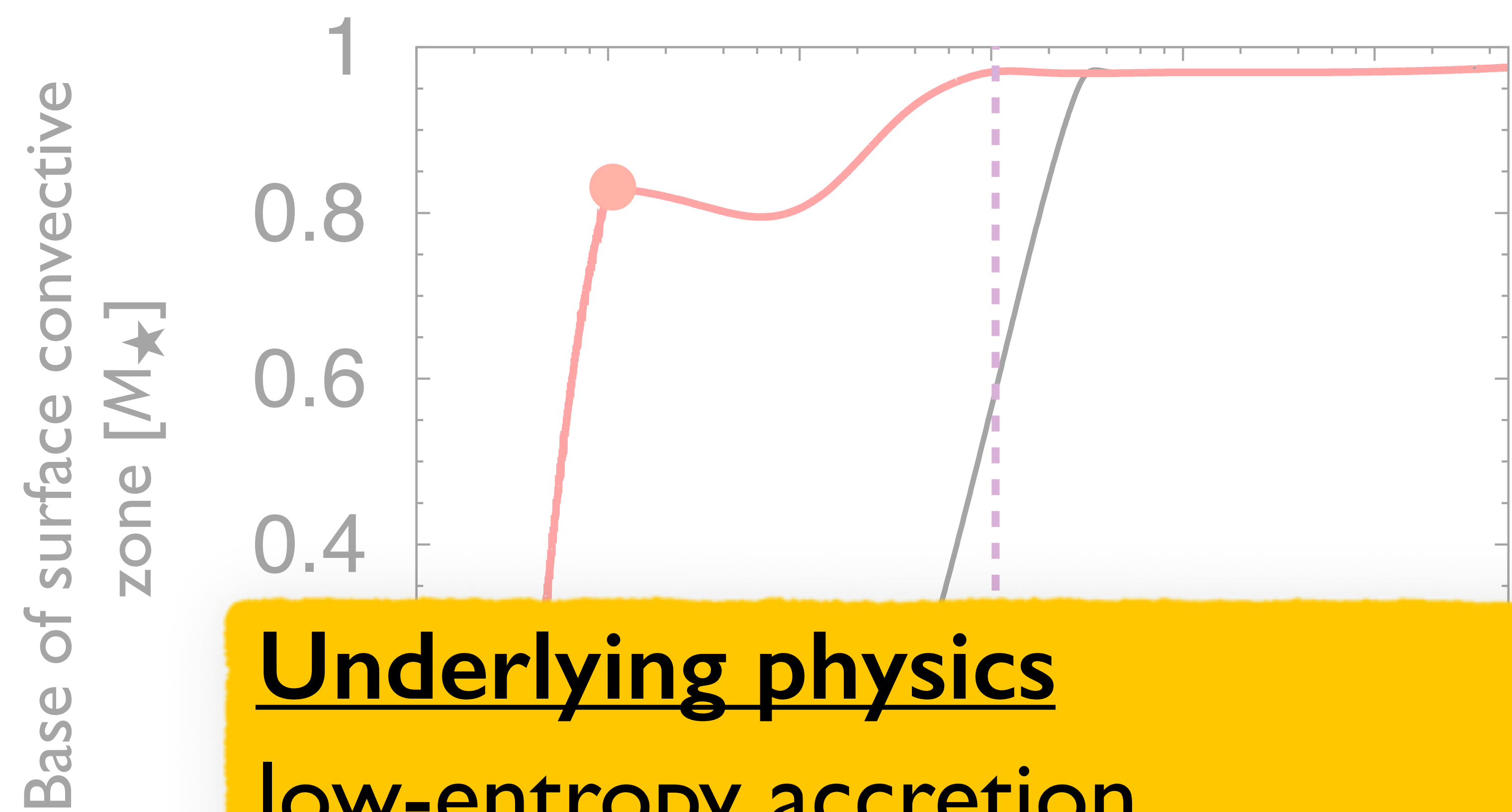
- With ξ=0, the surface CZ shrinks rapidly **even before disk dispersal!**

Baraffe+Chabrier10

- With the standard evolution, it takes ~30Myr

Pollution of stellar surface is expected to be stronger in the low-entropy accretion cases, if planets are formed

Internal structure with low-entropy acc.



- With ξ=0, the surface CZ shrinks rapidly **even before disk dispersal!**

Baraffe+Chabrier10

<u>Underlying physics</u>

low-entropy accretion

→ smaller radius

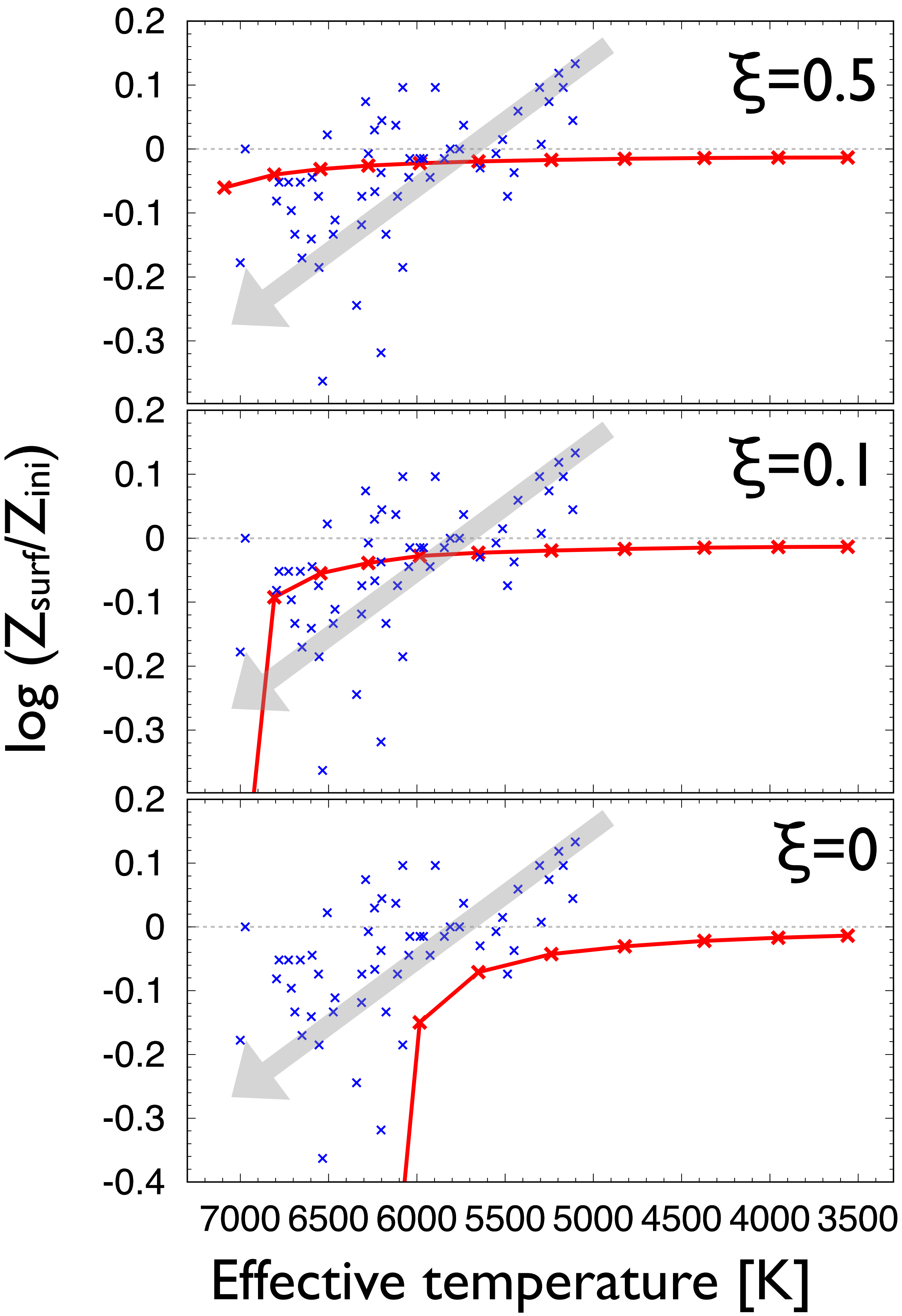
→ higher temperature (From Virial theorem, $T \propto M/R$)

→ smaller opacity

→ radiative core develops

(cf. in Schwarzschild criterion, convective if $\nabla_{\rm ad} < \nabla_{\rm rad} \propto \kappa l$)

Metallicity gradient in Hyades cluster



Red lines:

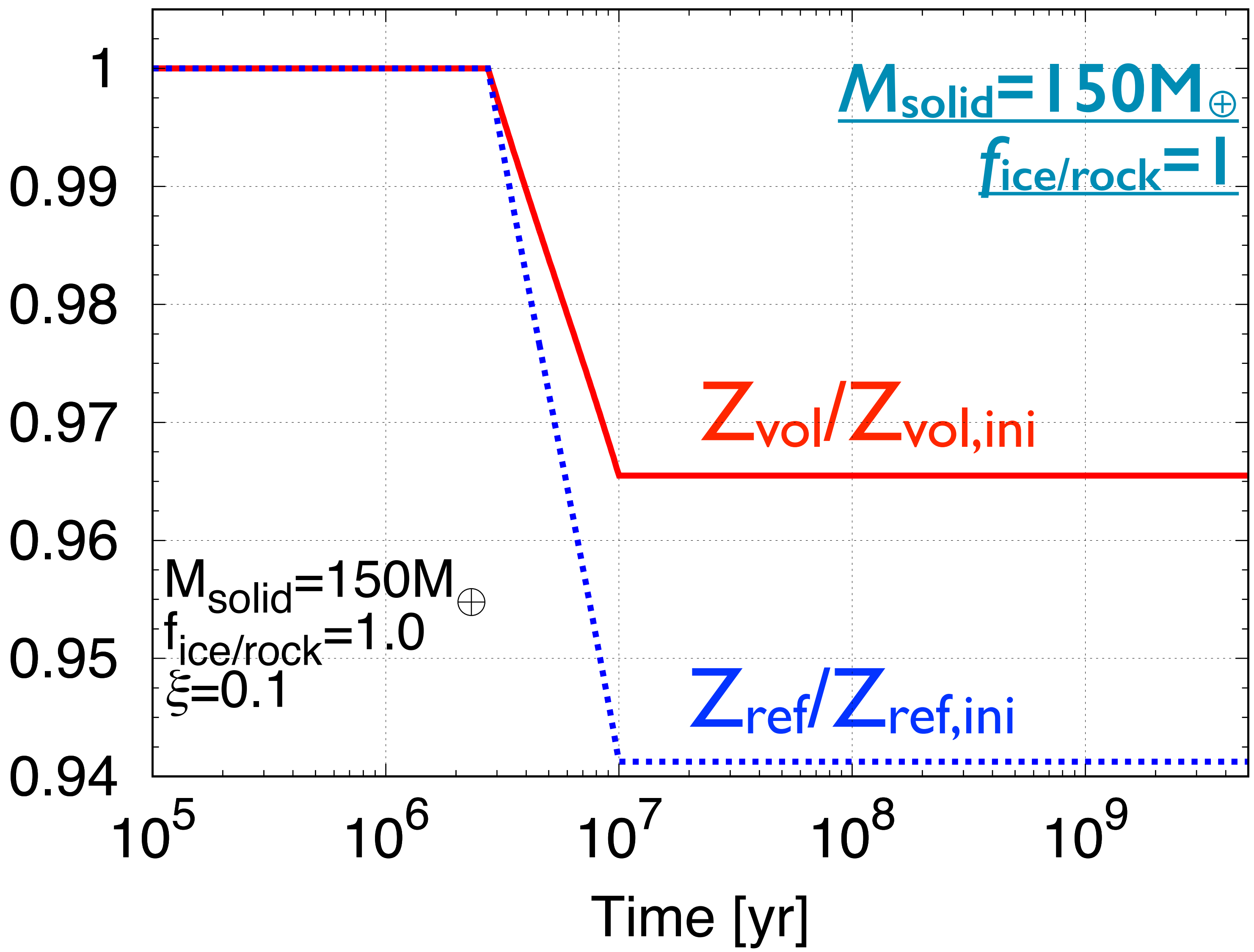
Consequences of planet formation

- **Metal-free accretion for $0.03M_{fin}$**
- **higher-mass stars have shallower convective zone ➔ larger impact**

The trend made by planet formation does not match the observation with any ξ value

➔ planet formation process is not the origin

Solar composition anomaly



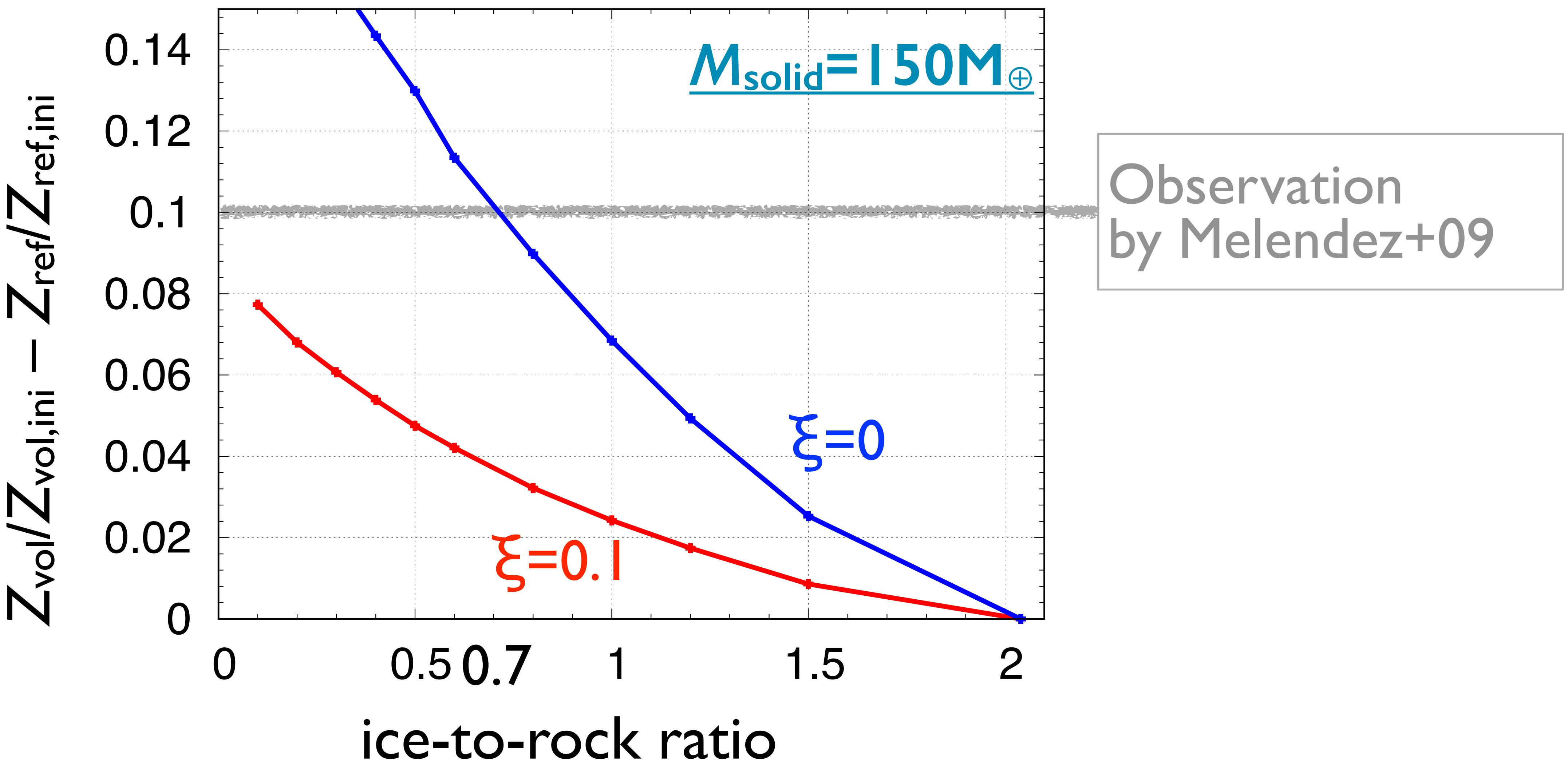
Heavy elements { Volatile / Refractory

~2%

With lower $f_{ice/rock}$ than 2 (=solar photosphere value), more refractory elements are deposited in planets

➔ refractory-poor accretion

Solar composition anomaly



- With ξ=0.1 and M_{solid}=150M⊕, any ice-to-rock ratio value cannot reproduce the observed refractory-poor composition
- With ξ=0 and $f_{ice/rock}$=0.7, planet formation can be the origin of the composition anomaly
  - With M_{solid}=100 and 200M⊕, $f_{ice/rock}$**=0.5–0.85**

Summary

We revisited pre-MS evolutions with low-entropy accretion and found

(1) Stars formed by the low-entropy accretion have a much smaller radius and luminosity and develop a radiative core more rapidly

(2) Luminosity spreads of pre-MS stars can be explained by different heat injection ξ

(3) Most (~90%) stars may be formed with $\xi > 0.1$

(4) Planet formation cannot explain the *metallicity gradient in Hyades cluster*, but can explain the *solar composition anomaly* if $\xi = 0$ and $f_{\text{ice/rock}} \sim$ **0.5–0.85** are possible

(5) Multidimensional RHD simulations are needed to reveal the heat injection efficiency ξ